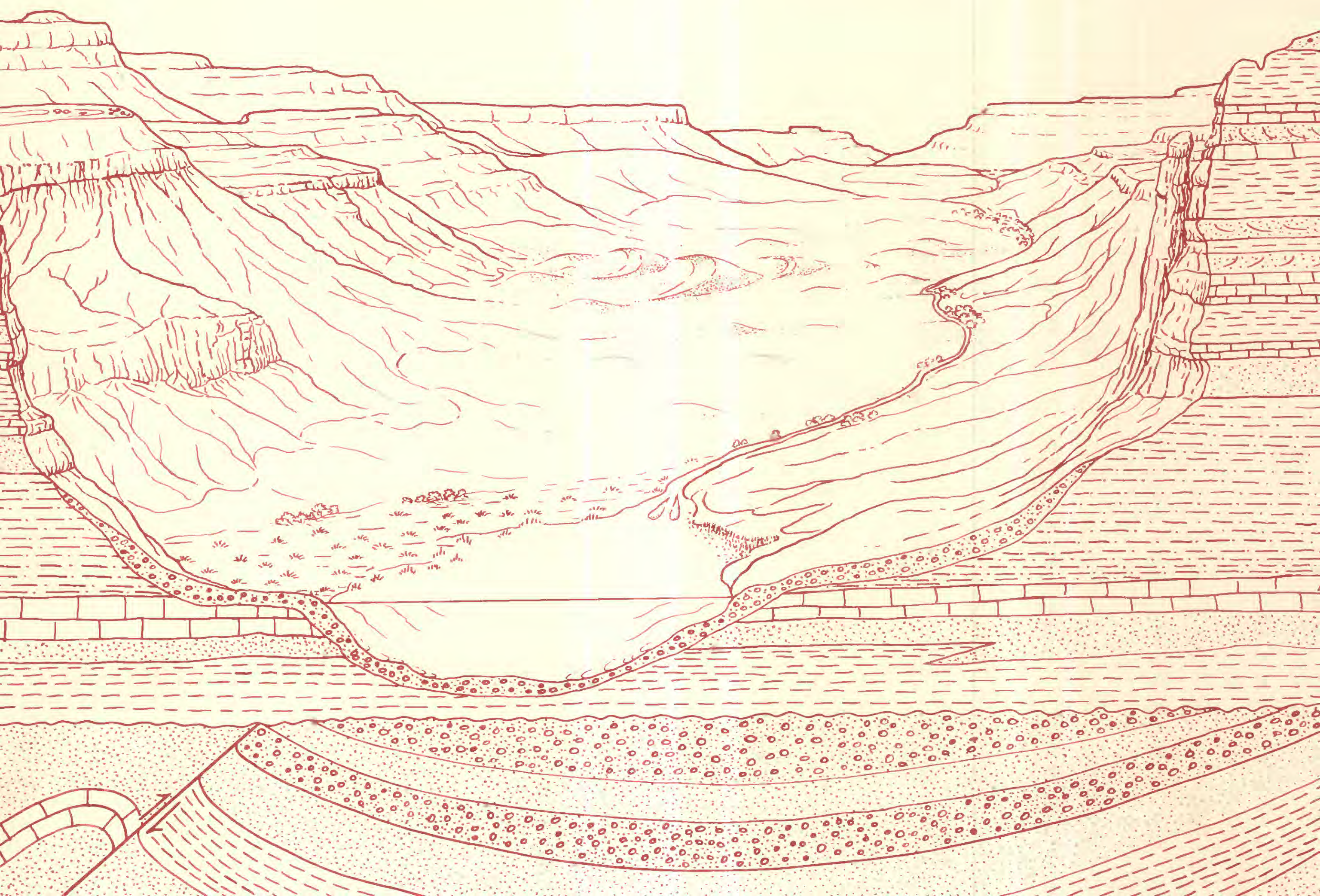
Revisions of Middle Jurassic Nomenclature in the Southeastern San Juan Basin, New Mexico

Eolian and Noneolian Facies of the Lower Permian Cedar Mesa Sandstone Member of the Cutler Formation, Southeastern Utah

U.S. GEOLOGICAL SURVEY BULLETIN 1808–E,F



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By STEVEN M. CONDON

Eolian and Noneolian Facies of the Lower Permian Cedar Mesa Sandstone Member of the Cutler Formation, Southeastern Utah

By JOHN D. STANESCO and JOHN A. CAMPBELL

Chapters E, F are issued as a single volume and are not available separately

U.S. GEOLOGICAL SURVEY BULLETIN 1808–E,F

EVOLUTION OF SEDIMENTARY BASINS—SAN JUAN BASIN

DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

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Chapter E

Revisions of Middle Jurassic Nomenclature in the Southeastern San Juan Basin, New Mexico

By STEVEN M. CONDON

Prepared in cooperation with the Pueblo of Laguna

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1808

EVOLUTION OF SEDIMENTARY BASINS—SAN JUAN BASIN

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CONVERSION FACTORS FOR SOME SI METRIC AND U.S. UNITS OF MEASURE

To convert from	To	Multiply by
Feet (ft)	Meters (m)	0.3048
Miles (mi)	Kilometers (km)	1.609
Pounds (lb)	Kilograms (kg)	0.4536
Degrees Fahrenheit (°F)	Degrees Celsius (°C)	Temp °C = (temp °F–32)/1.8

Revisions of Middle Jurassic Nomenclature in the Southeastern San Juan Basin, New Mexico

By Steven M. Condon

Abstract

A dominantly eolian sandstone sequence that lies at the top of the Middle Jurassic Wanakah Formation and at the base of the Upper Jurassic Morrison Formation in the area of Mesita, N. Mex., has been given different names by different workers. Most recently, the entire sequence was called the Bluff Sandstone or sandstone at Mesita, or was divided into the Bluff Sandstone and the Zuni Sandstone. A sandstone having similar characteristics also crops out to the west of Mesita in the Gallup area. This sandstone is divided into an Upper Jurassic part, included with the Recapture Member of the Morrison Formation, and a Middle Jurassic part, assigned to the Cow Springs Sandstone of the San Rafael Group.

In this report, the sandstone in the Mesita area is likewise divided into an upper part, included with the Recapture Member of the Morrison Formation, and a lower part, recognized as a southward extension of the Horse Mesa Member of the Wanakah Formation. These revisions in nomenclature make the contact between Middle and Upper Jurassic units consistent throughout much of the San Juan basin and recognize a widespread eolian sandstone at the base of the Morrison Formation in the southern part of the basin.

INTRODUCTION

The name Bluff Sandstone has been used to denote a thick sandstone that crops out in much of southeast Utah, northeast Arizona, and northwest New Mexico. In most places, this sandstone is underlain by the Middle Jurassic Wanakah Formation and is overlain by the Salt Wash or Recapture Members of the Upper Jurassic Morrison Formation. The Bluff was interpreted to be equivalent to part of the Middle Jurassic Cow Springs Sandstone (Harshbarger and others, 1951).

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O'Sullivan (1980) demonstrated, however, that the Bluff Sandstone, at Bluff in southeast Utah, is the lowest member of the Morrison Formation in that area and therefore is Late Jurassic in age. The Bluff is now viewed as being younger and not equivalent to any part of the Cow Springs. The revised interpretation of the Bluff in southeast Utah initiated a reevaluation of all the rocks called Bluff in northeast Arizona and northwest New Mexico that resulted in some revisions of stratigraphic nomenclature (Condon and Huffman, 1988).

This report summarizes additional stratigraphic studies on the Bluff Sandstone along the south rim of the San Juan basin and in the Acoma sag (fig. 1). As a result of these studies, the name Bluff Sandstone is no longer used in this area. The lower part of the former Bluff is recognized as the Horse Mesa Member of the Wanakah Formation. The upper part of the former Bluff, also assigned by some to the Zuni Sandstone in this area, is considered to be Late Jurassic in age and is assigned to the Recapture Member of the Morrison Formation. The revised correlations along the south rim of the San Juan basin are shown in figure 2.

Acknowledgments.—Thanks are extended to the people of the Pueblo of Laguna for permission to study the rocks described in this report that occur on their land.

GEOLOGIC SETTING

The regional structural setting of the study area is on the southeast side of the Colorado Plateau (fig. 1). Jurassic rocks crop out there in an arcuate band that extends across five structural elements: the Lucero and Zuni Mountain uplifts, San Juan basin, and Acoma and Gallup sags (fig. 3). Jurassic rocks in the study area are underlain by the Triassic Chinle Formation and are overlain by the Cretaceous Dakota Sandstone (fig. 4).

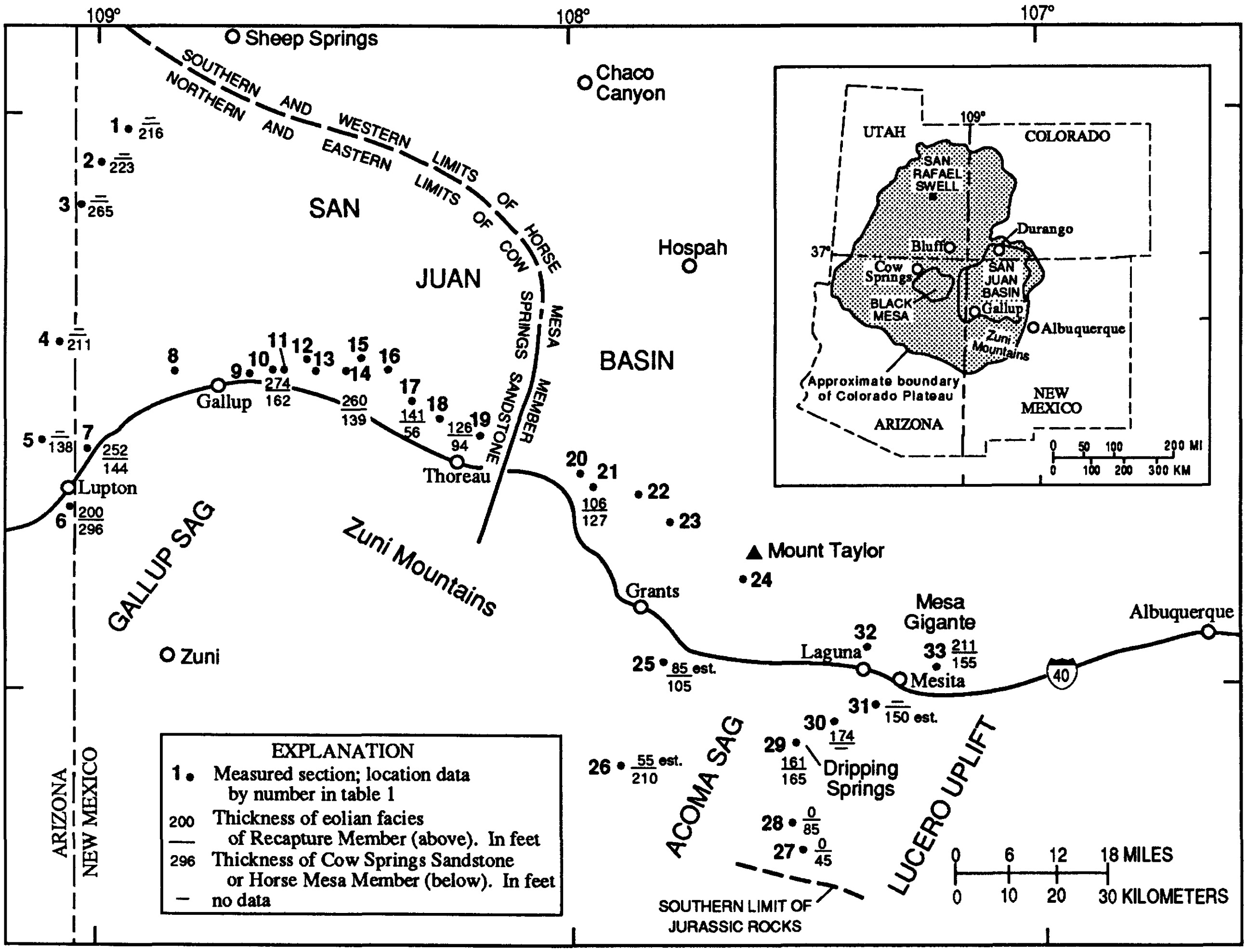


Figure 1. Location of measured sections and thicknesses of the Recapture Member of the Morrison Formation, Cow Springs Sandstone, and Horse Mesa Member of the Wanakah Formation, San Juan basin area of New Mexico and Arizona. Detailed section location information in table 1.

The Lucero uplift is a westward-tilted fault block; its present geometry is a result of Laramide and younger tectonic events (Callender and Zilinski, 1976, p. 53–59). The uplift is at the boundary between the Colorado Plateau to the west and the Rio Grande rift to the east.

The San Juan basin is a large, asymmetric structural and topographic depression, the axis of which lies approximately along the Colorado-New Mexico State line, well north of the study area. Strata on the northern side of the basin dip steeply southward, and those on the southern side dip gently northward. The basin is surrounded by uplifts and monoclines (fig. 3).

The Acoma sag is a southeast-extending embayment of the San Juan basin that lies between the Zuni uplift to the west and the Lucero uplift to the east. The sag is an asymmetric, northward-plunging trough; its steeper flank is on the west. Jurassic rocks are exposed on both sides of the structure. The Gallup sag is a similar embayment on the southwestern side of the San Juan basin that lies between the Zuni and Defiance uplifts (fig. 3).

The Zuni uplift is a northwest-trending asymmetric anticline; its steeper flank is on its west-southwest side. Precambrian crystalline rocks are exposed in the core of the anticline, and Paleozoic and younger rocks are exposed in concentric outcrops around its flanks.

PREVIOUS STUDIES

The study area has a long history of geologic investigations because of its location along a major transcontinental transportation route and because of the presence of large deposits of uranium and other minerals. Some of the earliest descriptions were by Marcou (1856), Newberry (1861), Gilbert (1875), and Dutton (1885). Dutton's report is of interest because some of the nomenclature that he introduced is still in use today (fig. 4). In particular, Dutton (1885, p. 137) described a

Table 1. Locations of measured sections, San Juan basin, New Mexico and Arizona
[Locations of sections shown by number on figure 1]

Section number and name	Location Sec.	T.	R.	Source
1. Todilto Park	13	20 N.	20 W.	Condon (1985a)
2. Navajo	31	20 N.	20 W.	Condon (1985a)
3. Twin Buttes Wash	30	19 N.	20 W.	Condon (1985a)
4. Pipeline Road	30	26 N.	31 E.	Condon (1985a)
5. Bowman Park	36	24 N.	30 E.	Condon (1985a)
6. Lupton East and West*	3	22 N.	31 E.	Condon (1985a); Craig and others (1959)
7. Manuelito	36	14 N.	21 W.	Condon (1985a)
8. Beal-Miller (drill hole)*	3	15 N.	19 W.	Saucier (1967)
9. Gallup*	7	15 N.	17 W.	Saucier (1967)
10. Pyramid Peak*	2	15 N.	17 W.	Saucier (1967)
11. Navajo Church	11	15 N.	17 W.	Condon (1985b)
12. White Rock Mesa*	31	16 N.	16 W.	Turner-Peterson and others (1980)
13. Fort Wingate*	4	15 N.	16 W.	Harshbarger and others (1957)
14. Midget Mesa	7	15 N.	15 W.	Condon (1985b)
15. Fallen Timber Ridge #1*	32	16 N.	15 W.	Turner-Peterson and others (1980)
16. Pinedale East and West (composite)*	1	15 N.	15 W.	A.R. Kirk and others (unpub. data, 1980)
17. Pinedale Monocline/Coolidge Quarry*	33	15 N.	14 W.	Condon (1985b); A.C. Huffman, Jr., and A.R. Kirk (unpub. data, 1980)
18. Thoreau West*	1	14 N.	14 W.	Turner-Peterson and others (1980)
19. East Thoreau*	13	14 N.	13 W.	Condon (1985b); Craig and others (1959); J.F. Robertson (unpub. data, 1983)
20. Goat Mountain*	2	13 N.	11 W.	Turner-Peterson and others (1980)
21. Haystack Mountain*	13,18,19	13 N.	11 W.	Condon (1985b); Craig and others (1959)
22. Blue Peak Mines*	24	13 N.	10 W.	Turner-Peterson and others (1980)
23. Red Bluff*	3	12 N.	9 W.	Freeman and Hilpert (1956)
24. Drill hole F*	12	11 N.	8 W.	Santos (1970, fig. 2)
25. Quemado Road	28	10 N.	9 W.	This report
26. The Narrows	33	8 N.	10 W.	This report
27. Wilson Ranch	19	6 N.	6 W.	This report
28. Petaca Pinta	12	6 N.	7 W.	This report
29. Dripping Springs	24	8 N.	7 W.	This report
30. South Butte	2	8 N.	6 W.	This report
31. Crow Mesa	4	8 N.	5 W.	This report
32. Laguna*	28	10 N.	5 W.	Craig and others (1959)
33. Mesa Gigante*	12	9 N.	4 W.	This report; Silver (1948); Craig and others (1959)

*Section used to construct figure 2.

sequence of sandstones and shales, 800–1,300 ft thick, that he termed the "Zuni sandstones." Just east of Gallup, near Navajo Church, this sequence lay between the Wingate Sandstone and the Dakota Sandstone and included rocks that were later divided into the Wanakah Formation, Cow Springs Sandstone, Bluff Sandstone, and Morrison Formation. The unit that Dutton (1885, p. 137) named the Wingate Sandstone is now recognized as the Entrada Sandstone, of Jurassic age, in the San Juan basin area. However, when Dutton examined similar rocks south of Gallup at Zuni Pueblo, he inadvertently placed the basal contact of the Zuni at the base of the Wingate (now Entrada), not at the top, as he had done at Navajo Church.

The next important report bearing on the nomenclature of this area was by Gregory (1917). Gregory (1917, p. 52) divided all rocks between the Triassic Chinle Formation and the Cretaceous Dakota Sandstone into two subdivisions, the Jurassic La Plata Group and the Jurassic(?) McElmo Formation.

The La Plata Group had previously been defined as the La Plata sandstone by Cross and Purington (1899) in southwest Colorado. It consisted of two massive sandstone beds separated by limestone and shale beds. Gregory (1917) correlated the lower sandstone of the La Plata Group with the Wingate Sandstone of Dutton (1885), and he named the overlying limestone and minor shale beds the Todilto Formation (Gregory, 1917, p. 55). The upper sandstone of the La Plata Group was named the Navajo Sandstone and was considered to be equivalent to the lower, massively bedded sandstone part of Dutton's (1885) Zuni sandstones at Navajo Church

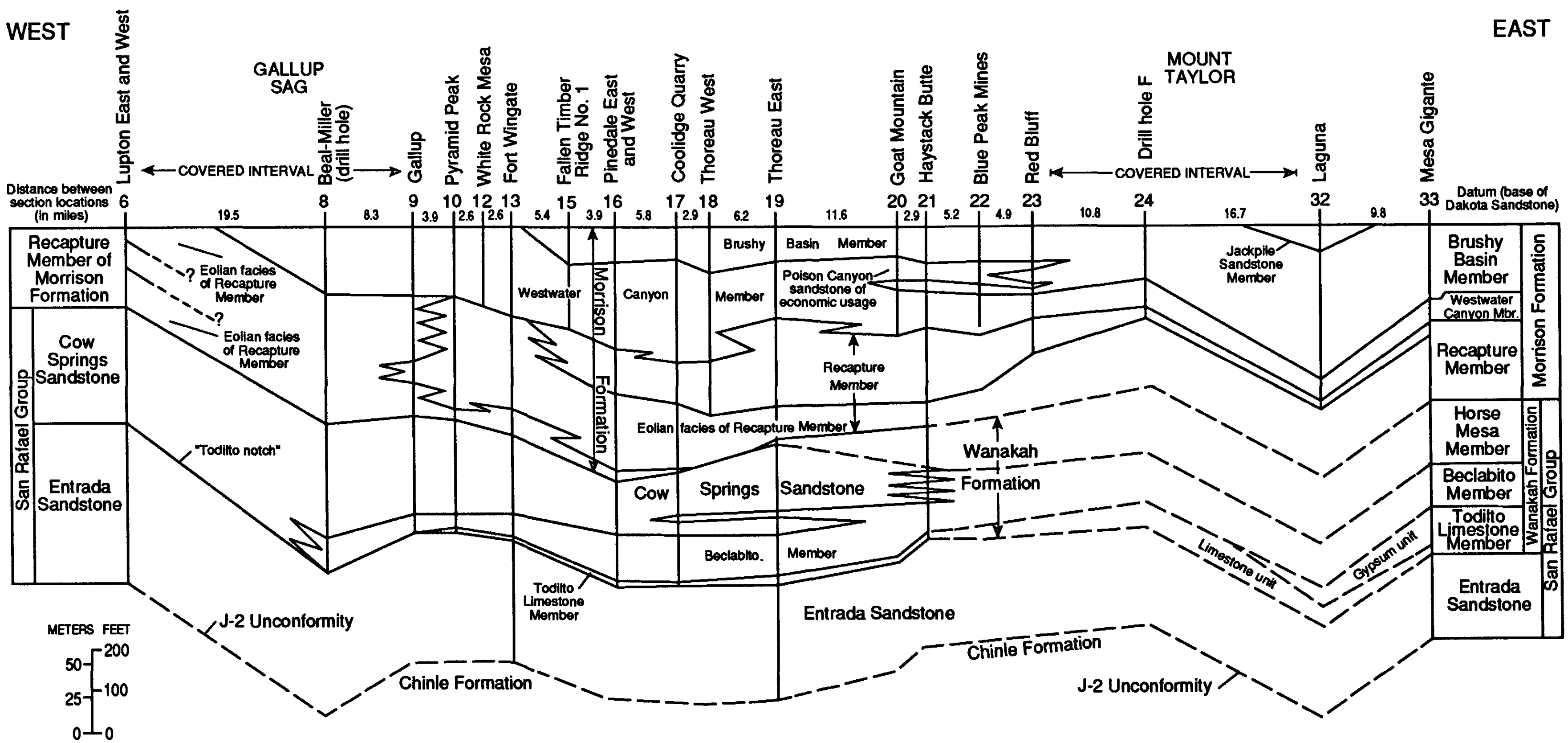


Figure 2. Revised correlations of Jurassic rocks in the Gallup sag, along the south rim of the San Juan basin, and in the Acoma sag. Detailed section location information in table 1; location of measured sections shown in figure 1. Modified from Condon and Peterson (1986).

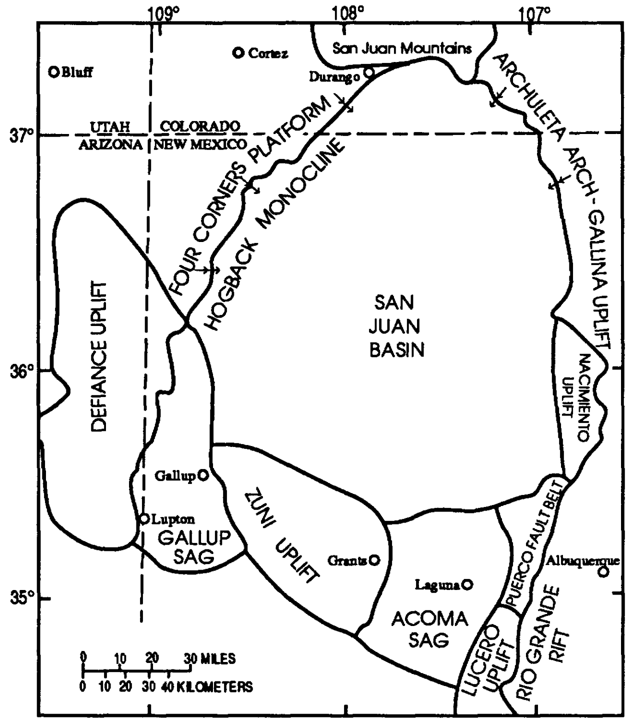


Figure 3. Structural elements in region of study area, San Juan basin. Modified from Kelley (1963).

(Gregory, 1917, p. 59). Today, the name La Plata Group has been abandoned, and the rocks comprising the former La Plata Group in Colorado have been divided into the Entrada Sandstone at the base, the Wanakah Formation, and the Junction Creek Sandstone at the top. Along much of the south rim of the San Juan basin, the former La Plata Group consists of the Entrada Sandstone, Wanakah Formation, and Cow Springs Sandstone.

The McElmo Formation was also originally defined by Cross and Purington (1899) in southwest Colorado. It consisted of a series of sandstones and shales above the La Plata Group and below the Dakota Sandstone. In today's nomenclature, the McElmo Formation of Cross and Purington (1899) is principally the Morrison Formation. Gregory (1917, p. 63) considered the large-scale crossbedded sandstone at Navajo Church to constitute the lower half of the McElmo Formation. The McElmo was separated from the underlying Navajo Sandstone by 38 ft of transitional beds at Navajo Church (Gregory, 1917, p. 61).

According to our current understanding of regional correlations, Gregory's Navajo Sandstone was miscorrelated from southeast Utah to northwest New Mexico and southwest Colorado. In southeast Utah, the Navajo Sandstone is recognized as a part of the Jurassic Glen Canyon Group (Gregory and Moore, 1931). The Glen Canyon Group of southeast Utah, similar to the abandoned La Plata Group, consists of two massive sandstone beds separated by shaley beds. The lower sandstone is the Wingate Sandstone, the shaley beds in the middle are the Kayenta Formation, and the upper sandstone is the Navajo Sandstone. The Glen Canyon Group, however, is stratigraphically older and lies below the former La Plata Group.

Darton (1922, 1928) also worked in this report area. He extended Gregory's (1917) correlation of the Todilto Formation and the overlying Navajo Sandstone into the areas north and east of the Zuni uplift. Darton used the name Morrison Formation to replace McElmo Formation (1922, p. 184; 1928, p. 139) and assigned the Morrison a Cretaceous(?) age.

Darton's interpretation of the Navajo Sandstone differed in some respects from Gregory's. In a cross section, Darton (1928, p. 139) showed that his Navajo Sandstone consisted of a basal white sandstone, a middle shaley interval, and an upper buff to red sandstone. The upper buff to red sandstone corresponds to what is now recognized as the Westwater Canyon Member of the Morrison Formation. The Morrison shale of Darton (1928, p. 139) is equivalent only to the Brushy Basin Member of the Morrison.

Baker and others (1936) reviewed the nomenclature of northwest New Mexico and other areas. They accepted the correlation of Dutton's (1885) Wingate Sandstone with the Wingate Sandstone of the Glen Canyon Group as used in Utah; however, they recognized the miscorrelation of the Navajo Sandstone from Utah to New Mexico and believed the Navajo to be absent in the Zuni uplift area (Baker and others, 1936, p. 5). The Wingate Sandstone was considered to be Jurassic(?) in age.

Baker and others (1936, p. 44) assigned all strata above the Wingate Sandstone in New Mexico (the Entrada Sandstone of present usage) to the Morrison Formation. The Morrison consisted of the Todilto Limestone Member at the base, a sandstone member, and a shale member. The sandstone member was shown as an equivalent of Darton's (1928) Navajo Sandstone (Baker and others, 1936, table 8). In northwest New Mexico, the Morrison was reported to be composed almost entirely of sandstone, and was considered to be equivalent to Dutton's Zuni Sandstone (Baker and others, 1936, p. 9). The Morrison was assigned a Jurassic age.

Subsequent stratigraphic studies caused Baker and others (1947) to significantly revise their earlier paper. In their revision, the upper part of Dutton's Wingate Sandstone was correlated with the Jurassic Entrada Sandstone, the middle part of Dutton's Wingate was considered the Carmel Formation, and only the lower part remained the Wingate Sandstone. (This last bit of Wingate was later renamed the Iyanbito Member of the Entrada Sandstone by Green, 1974). The Todilto Limestone Member was removed from the Morrison Formation and included in the Wanakah Formation

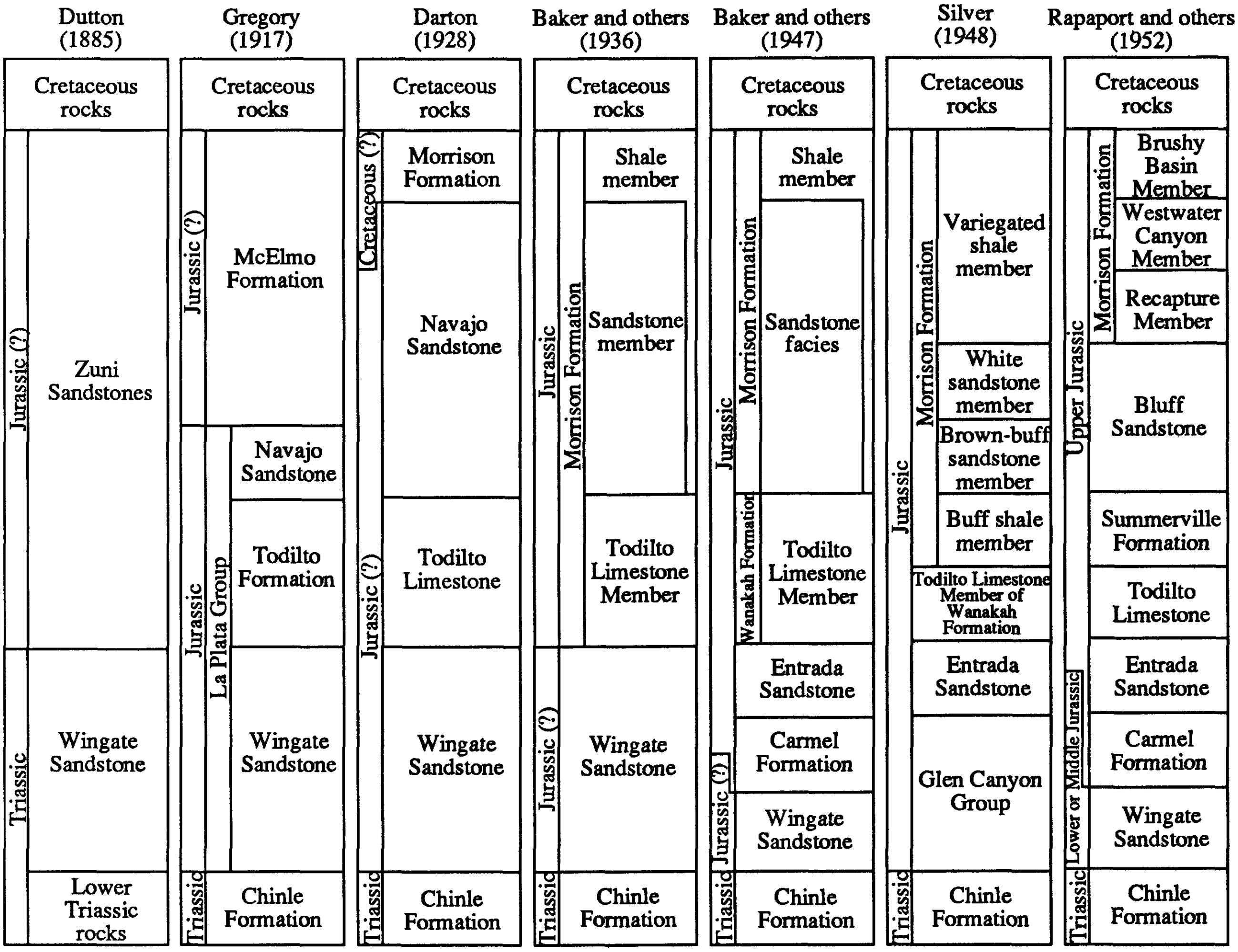


Figure 4 (above and facing page). Previous and present nomenclature for the southern San Juan basin and Gallup and Acoma sags.

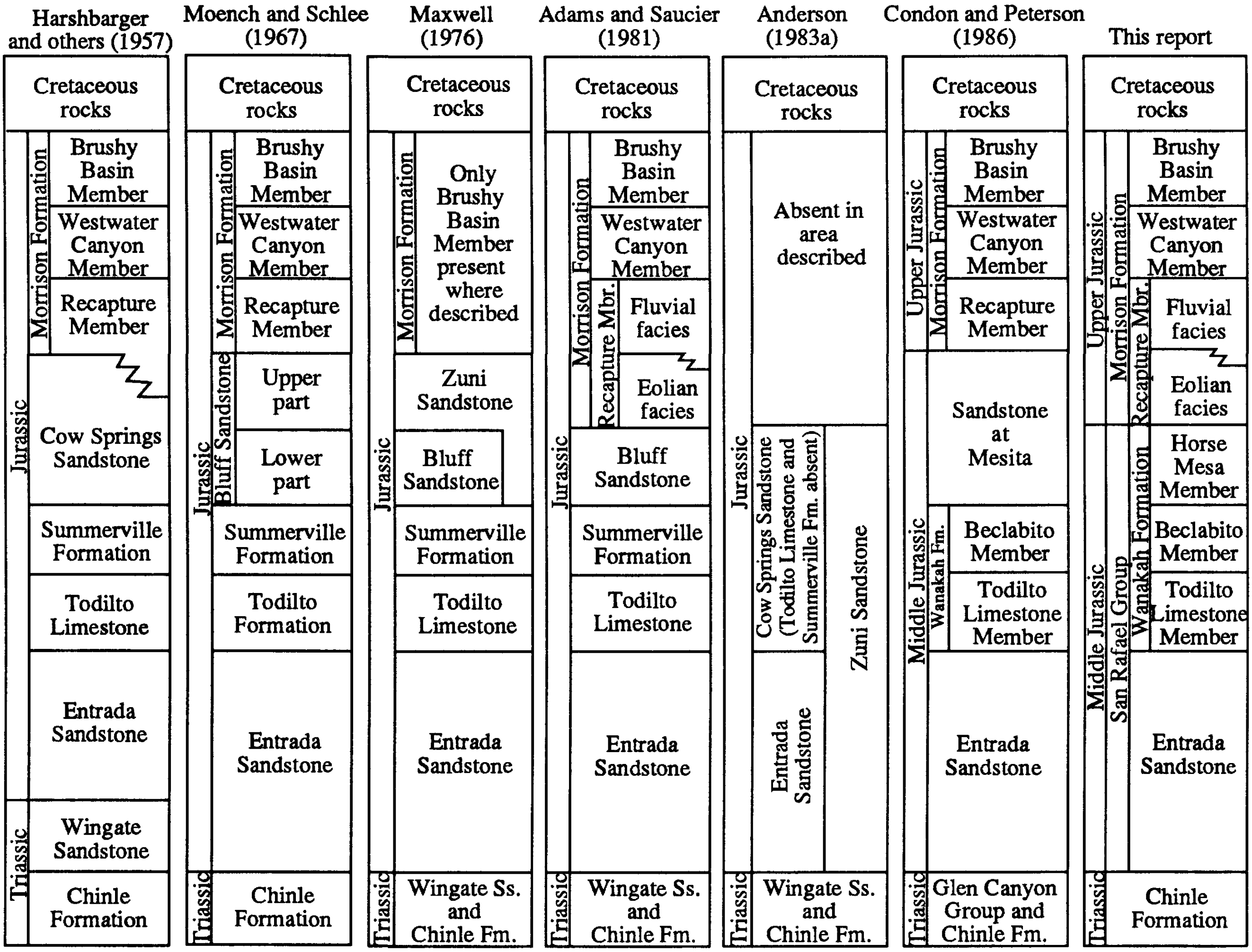
(Baker and others, 1947, p. 1668). This was the first time that the Wanakah Formation, which had earlier been defined by Burbank (1930) in Colorado, was recognized in New Mexico. The massive sandstone above the Todilto Limestone Member of the Wanakah, or above the Entrada Sandstone where the Todilto Limestone was not present, was considered a sandstone facies of the Morrison Formation (Baker and others, 1947, p. 1668).

The first paper concerned specifically with the Acoma sag was by Silver (1948), who traced Jurassic strata from Mesa Gigante in the north (fig. 1) to the southern limit of exposures of Jurassic rocks along the eastern side of the Acoma sag. (See table 1 for locations of measured sections.) Silver (p. 70) showed that Jurassic rocks thinned southward to a truncated edge. The thinning was caused both by onlap onto a Jurassic positive area and by subsequent erosion before deposition of overlying Cretaceous rocks (Silver, 1948, p. 81).

The beds included in the Morrison Formation had been mapped previously by Kelley and Wood (1946) and consisted of the buff shale member at the base, the brown-buff sandstone member, the white sandstone member, and the variegated shale member at the top (Silver, 1948, p. 77). Both the Morrison Formation and the underlying strata above the Chinle Formation were considered as Jurassic in age.

The buff shale member rested on the Todilto Formation (now Todilto Limestone Member of the Wanakah Formation) and was composed of as much as 130 ft of interbedded white, buff, red, red-brown, and pale-green, thinly bedded sandstone, shale, and siltstone. This member was mainly shale and siltstone near Mesa Gigante and changed southward to sandstone and siltstone. The basal bed of the buff shale member graded to a pebble conglomerate in the southernmost exposures. Silver (1948, p. 77) mentioned that the buff shale member would possibly have been included in the Wanakah Formation by Baker and others (1947).

The brown-buff sandstone member was described by Silver (1948, p. 78) as a sandstone 65–90 ft thick that formed a bold cliff near the present village of Mesita (fig. 1). The member was buff to brown or dark brown,



fine to medium grained and evenly bedded, and had irregularly developed crossbedding. Silver traced the member southward from Mesa Gigante to Dripping Springs (fig. 1), where it was indistinguishable from the overlying member. Silver believed the member thinned and graded southward into the overlying sandstone beds.

The white sandstone member was about 200 ft of buff, white, yellow, and greenish-gray, medium- to fine-grained, conspicuously crossbedded sandstone. Its thickness increased slightly southward at Dripping Springs (probably because the underlying brown-buff sandstone member was included with it) and decreased from Dripping Springs to the south.

The variegated shale member was the uppermost member of the Morrison Formation of Silver and consisted of as much as 275 ft of white, gray, green, and purple claystone, siltstone, and sandstone. Silver (1948, p. 78) interpreted this member to thin and grade southward into a white sandstone that was nearly indistinguishable from the underlying white sandstone member.

In the 1950's, stratigraphic studies concentrated mainly on the uranium-bearing rocks of the Colorado Plateau, including those discussed herein. Rapaport and others (1952) reported on the Zuni uplift and established much of the Jurassic nomenclature subsequently used in that region. Their stratigraphy consisted of the following formations, from oldest to youngest: the Wingate Sandstone, the Carmel Formation, the Entrada Sandstone, the Todilto Limestone, the Summerville Formation, the Bluff Sandstone, and the Morrison Formation. The Todilto Limestone was again recognized as a separate formation, as originally defined by Gregory (1917). The Todilto was correlated with equivalent limestone beds in the Wanakah Formation of Colorado. The names Summerville Formation and Bluff Sandstone were introduced for the first time into west-central New Mexico from southeastern Utah. The name Wanakah Formation was not used by Rapaport and others (1952).

The Summerville Formation had been defined by Gilluly and Reeside (1928) for exposures in the San Rafael Swell in east-central Utah, and was correlated into southeast Utah by Baker and others (1936). The Summerville was the uppermost formation of the newly defined San Rafael Group that originally consisted of, in ascending order, the Carmel Formation, Entrada Sandstone, Curtis Formation, and Summerville Formation (Gilluly and Reeside, 1928, p. 73).

Rapaport and others (1952, p. 27) correlated the Summerville into the Zuni uplift from Utah along Jurassic exposures on the west side of the San Juan Basin. They believed (p. 28) that the similarity of lithologies, analogous facies changes, and the position of the beds above the Todilto Limestone, coupled with evidence that the basin of deposition probably curved to the southeast, were sufficient reasons for introducing the Summerville into the Zuni uplift. The Summerville Formation is the same as the buff shale member of the Morrison Formation of Silver (1948).

The Bluff Sandstone (Baker and others, 1936; Gregory, 1938) had also been defined in southeast Utah. Gregory (1938, p. 36) considered the Bluff to be the lowest member of the Morrison Formation. Rapaport and others (1952) considered the Bluff to be a separate formation that intertongued with both the underlying Summerville Formation and with the overlying Morrison Formation in the Zuni uplift. The Bluff of the Zuni uplift was believed to correlate with the Bluff Sandstone of southeast Utah on the basis of its lithology and its stratigraphic position with respect to overlying and underlying formations. The Bluff Sandstone of the southeast San Juan basin had been termed the brown-buff sandstone and the white sandstone members of the Morrison Formation by Silver (1948).

Harshbarger and others (1951, 1957) added another name to the list of Jurassic units near the Zuni uplift. This was the Cow Springs Sandstone, and it had been defined in northeast Arizona. The Cow Springs is a greenish-gray to light-yellowish-gray, fine-grained, well-sorted, crossbedded and flatbedded, massive sandstone. Harshbarger and others (1951, p. 98) believed that the Summerville Formation graded laterally southward from Utah into the lower part of the Cow Springs and that the Bluff Sandstone and the lower members of the Morrison Formation graded southward into the upper part of the Cow Springs. The Bluff Sandstone in southeast Utah was believed to be a northward-extending tongue of the Cow Springs.

Harshbarger and others (1951, 1957) correlated the Cow Springs southeastward from Arizona into the southwestern part of the San Juan Basin and then eastward along the southern rim of the basin. The main Cow Springs was thought to have fed several tongues of eolian sandstone that extended outward from the unit, the older Bluff Sandstone and the younger "white sandstone" tongues being most conspicuous. They noted (1957, p. 48) that the white sandstone tongue was the basal unit of the Morrison Formation in some areas, and that Kelley and Wood (1946) and Silver (1948) had described a similar white sandstone member of the Morrison in the southeastern part of the San Juan basin. They also noted (1957, p. 48) that in some areas the Cow Springs was equivalent to the Zuni Sandstone of Dutton (1885).

Moench and Schlee (1967) made minor revisions to Jurassic nomenclature in the Laguna-Mesita area based on extensive mapping, and their report included a thorough discussion of the Bluff Sandstone of that area. The Bluff Sandstone was considered by Moench and Schlee (1967, p. 15) to be equivalent to the brown-buff and white sandstone members of the Morrison Formation of Kelley and Wood (1946) and Silver (1948).

Moench and Schlee (1967, p. 15–17) divided the Bluff Sandstone into distinctive parts. The lower part is pale-reddish-brown to pale-orange, very fine to medium grained, fairly well sorted sandstone. Alternating thin to very thick, flatbedded and crossbedded sandstone strata characterize the unit. Crossbedding in the lower part is mostly small to medium scale. Transport directions, as indicated by crossbed dip directions, are scattered fairly evenly between northeast and southeast quadrants. The mean of 81 measurements of transport direction was calculated as S. 87° E. (Moench and Schlee, 1967, p. 15). The lower part of the Bluff Sandstone intertongues with the underlying Summerville Formation (now Wanakah Formation) and is overlain gradationally by the upper part of the Bluff.

The upper part of the Bluff Sandstone of Moench and Schlee (1967) is yellowish-gray, grayish-yellow, and grayish-yellow-green, fine- to medium-grained, very well sorted sandstone. Spectacular, large to very large scale crossbed sets are characteristic of the upper part. The sets dip consistently northeastward; the average of 63 dip readings was calculated as N. 78° E. (Moench and Schlee, 1967, p. 16). Because of its large-scale, high-angle crossbeds, this part of the Bluff Sandstone is believed to have an eolian origin (Moench and Schlee, 1967). The upper part intertongues with the overlying Recapture Member of the Morrison Formation.

Maxwell (1976, 1982) also did field studies in the Acoma sag. Although his use of Jurassic nomenclature was essentially the same as that of Moench and Schlee (1967), he defined the Bluff Sandstone differently. In Maxwell's usage, the lower part of the Bluff Sandstone of Moench and Schlee was termed the Bluff Sandstone, but the upper part was named the Zuni Sandstone. Maxwell's (1976, p. 98) descriptions of the Bluff and Zuni Sandstones correspond well with the descriptions of the upper and lower Bluff Sandstone by Moench and Schlee. Maxwell believed that the Bluff and Zuni Sandstones merged southward and became indistinguishable. Where only one unit was recognized, it was termed the Zuni Sandstone. As shown on figure 4, Maxwell's use of the name Zuni Sandstone is a restriction of Dutton's (1885) definition.

Saucier (1967) and Adams and Saucier (1981) also conducted stratigraphic studies of Jurassic rocks of the Zuni uplift. Although they worked mainly to the west of the Mesita area, near Gallup, their observations add an important dimension to an understanding of Jurassic rocks in the study area.

Adams and Saucier (1981, p. 22) reported that the Recapture Member of the Morrison Formation is composed of three facies. One facies consists of fine-grained, lenticular sandstone beds that were deposited by small meandering streams. Another facies, deposited in small playa lakes, is composed of fine-grained, thin-bedded sandstone beds interbedded with siltstone and mudstone beds. The third facies, which in places comprises almost the entire Recapture Member, consists of pale-red to grayish-yellow, very fine to fine-grained sandstone. The distinguishing feature of this third facies is the presence of very large scale crossbed sets, as thick as 80 ft, that have consistent crossbed dip directions to the east. This facies is interpreted as eolian in origin (Saucier, 1967). The underlying Cow Springs Sandstone or "Bluff Sandstone" was recognized by Adams and Saucier as a separate eolian sandstone.

Saucier's (1967) and Adams and Saucier's (1981) interpretation of the Recapture is important to the present study because of the equivalence of the eolian beds of the Recapture near Gallup to the upper part of the Bluff Sandstone of Moench and Schlee (1967) and to the Zuni Sandstone of Maxwell (1976, 1982) in the Acoma sag area. The units occupy the same stratigraphic position, have the same lithology and distinctive very large scale crossbedding, and display northeast transport directions.

Anderson (1983a, b) reviewed and summarized past use of the name Zuni Sandstone in New Mexico, including the area of this report. He noted that although some workers following Dutton had applied the name Zuni Sandstone, their usage of the term only added more complexity to the already ill-defined formation.

Anderson (1983a, b) recommended that the name Zuni Sandstone be retained, but restricted in areal extent to the southern Gallup sag. Anderson also advocated a clarification of which strata the Zuni Sandstone should include. In Anderson's usage the Zuni is equivalent to the undivided Entrada and Cow Springs Sandstones where other intervening stratigraphic units such as the Todilto Limestone or the Summerville Formation (now Wanakah Formation) are absent. Anderson's Zuni Sandstone is therefore the same as Dutton's Zuni in the Zuni Pueblo area but is different from both Dutton's (1885) and Maxwell's (1976, 1982) Zuni in other areas. Anderson's usage is adopted in this report, and the name Zuni Sandstone is restricted to the Zuni Pueblo area. The unit consists of rocks equivalent to the undifferentiated Cow Springs and Entrada Sandstones in the areas where those units are indistinguishable.

Studies in southeast Utah have influenced recent nomenclature changes in northwest New Mexico. O'Sullivan (1980) found that the correlation of the Summerville Formation from east-central Utah to southeast Utah by Baker and others (1936) was incorrect. As a consequence, the name Wanakah Formation was extended from southwest Colorado into southeast Utah to replace the name Summerville. O'Sullivan (1980) established that the Wanakah was largely older than the Summerville Formation.

Additionally, O'Sullivan (1980) decided that Gregory's (1938) original inclusion of the Bluff Sandstone as a member of the Morrison Formation was merited. The rank of the Bluff Sandstone was changed by O'Sullivan, and it is now again considered as the basal member of the Upper Jurassic Morrison Formation and is not equivalent to any part of the Middle Jurassic Cow Springs Sandstone.

Following stratigraphic studies in northeast Arizona and northwest New Mexico, Condon and Huffman (1988) made further revisions. In order to unify the nomenclature of southeast Utah, southwest Colorado, northeast Arizona, and northwest New Mexico, the name Wanakah Formation was extended southward into Arizona and New Mexico. The Wanakah was divided into three members, in ascending order, the Todilto Limestone Member, the Beclabito Member, and the Horse Mesa Member.

The Todilto Limestone was lowered in rank to a member of the Wanakah because its equivalent in Colorado, the Pony Express Limestone, is the basal member of the Wanakah. This assignment of the Todilto to the Wanakah is the same as that of Baker and others (1947).

The Beclabito Member of the Wanakah was introduced to replace the name Summerville Formation. The Beclabito is an exact equivalent of the Summerville as previously recognized in Arizona and New Mexico.

The Horse Mesa Member of the Wanakah replaces the Bluff Sandstone in the Carrizo Mountains area of the northwestern part of the San Juan basin, although both units are present in some places in northeast Arizona, southeast Utah, and southwest Colorado. Stratigraphic and sedimentological studies show that the Horse Mesa Member has a gradational contact with the underlying Beclabito Member, although it is lithologically similar to the Bluff Sandstone Member of the Morrison. In at least one locality in northeast Arizona, the Horse Mesa and the Beclabito both display large folds, whereas the overlying Bluff Sandstone Member is undeformed. (See Condon and Peterson, 1986, fig. 14, and Condon and Huffman, 1988, fig. A4–B.) This indicates a close structural relationship between the Horse Mesa and the

Beclabito Member and also indicates that the overlying Bluff Sandstone Member of the Morrison is unrelated to the Horse Mesa Member. The Horse Mesa is interpreted as an equivalent of the upper Cow Springs Sandstone.

Condon and Huffman (1984) and Condon and Peterson (1986) also recognized a widespread eolian facies in the Recapture Member of the Morrison Formation. Condon and Peterson (1986, p. 9) divided the thick sandstone above the Wanakah Formation in the Gallup area into two parts. The lower part is assigned to the Cow Springs Sandstone and the upper part is assigned to the Recapture Member of the Morrison. On the southeast side of the basin, this sandstone at the top of the Wanakah was informally termed the "sandstone at Mesita." The "sandstone at Mesita" was equivalent to the upper and lower parts of the Bluff Sandstone of Moench and Schlee (1967) and to the Bluff and Zuni Sandstones of Maxwell (1976) (fig. 4).

At the time of Condon and Peterson's (1986) report, the relationship of the "sandstone at Mesita" to the Morrison Formation had not been studied in detail. Subsequent field studies now indicate that the upper part of the "sandstone at Mesita" is an eolian facies of the Recapture Member of the Morrison Formation and the lower part of the "sandstone at Mesita" is equivalent to the Cow Springs Sandstone and to the Horse Mesa Member of the Wanakah Formation.

METHODS OF STUDY

The data for this study were collected by measuring detailed sections of stratigraphic intervals of interest. Each section was measured with an Abney level and Jacob staff, where possible. In areas of steep cliffs, a 10-ft steel tape or 100-ft cloth tape was used.

Data were recorded on standardized forms that include columns for porosity, lithology, grain size, sorting, sedimentary structures, transport directions, and other parameters (see appendix). The measured sections used for control in the Gallup sag and southern San Juan basin have been published elsewhere (Condon, 1985a, b). Table 1 gives the locations of the measured sections; some measured sections used to construct figure 2 were drawn from the literature.

STRATIGRAPHY

Todilto Limestone and Beclabito Members of the Wanakah Formation

In the study area, the Wanakah Formation consists of three members, the basal Todilto Limestone Member, the Beclabito Member, and the Horse Mesa Member. The Todilto is composed of medium- to dark-gray, carbonaceous, thinly laminated to thin-bedded limestone and gypsum. In a typical exposure at Mesita, N. Mex., the limestone is about 15 ft thick. The Todilto gradationally overlies the Entrada Sandstone, and at the contact a few thin beds of calcareous sandstone or siltstone are commonly interbedded with limestone. At Mesita, about 110 ft of white, crudely bedded gypsum having a "chickenwire" texture overlies the limestone. The gypsum pinches out a short distance southwest of Mesita (Moench and Schlee, 1967, p. 11). The limestone thins and also pinches out southwest of Mesita (Maxwell, 1976, p. 96). The Todilto is interpreted to have been deposited in a restricted marine embayment (Ridgley and Goldhaber, 1983; Ridgley, 1984) or in a landlocked salina (Lucas and others, 1985).

The Beclabito Member of the Wanakah is composed of reddish-brown to white, silty sandstone, sandy siltstone, and claystone. The lithologies are interbedded and commonly form a steep slope or a series of ledges above the Todilto Limestone Member (fig. 5); the Beclabito ranges in thickness from a truncated edge in the south to about 125 ft at Mesita. Although the Beclabito is generally very fine to fine grained, it becomes coarser grained to the south and the basal beds grade southward into a chert-pebble conglomerate. Bedding is very thin to very thick, and individual beds have ripple cross laminations, small-scale crossbedding, and irregular, subhorizontal, wavy laminations or flat-bedding. Beds of the Beclabito are relatively thin but laterally extensive; exposures of the unit have a horizontally ruled appearance. Contorted bedding is common locally and may be the result of loading of unconsolidated sediment by overlying sand. In other places near Mesita, large breccia pipes disturb bedding in the Beclabito Member.

The Beclabito is interpreted as mainly marginal-marine or marginal-lacustrine and sabkha deposits that grade southward into fluvial deposits. Fluvial deposits are represented by chert-pebble conglomerate at the Wilson Ranch and The Narrows locations (fig. 1). At The Narrows the conglomerate sequence is as thick as 10 ft and is interbedded with crossbedded sandstone.

Most of the Beclabito was deposited on a low-lying area that was transitional between highlands to the south and the Todilto sea to the north. The very fine grained texture and lateral continuity of beds suggest deposition in a low-energy environment. A few beds of the Beclabito are composed of very well sorted, fine-grained sandstones that exhibit high-angle crossbedding characteristic of eolian dunes. These beds indicate deposition in an environment that was periodically subaerially exposed. Whether most of the Beclabito is marginal marine or

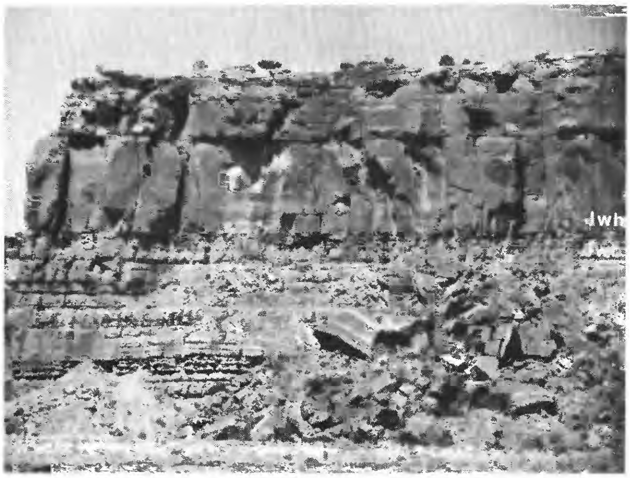


Figure 5. Horse Mesa and Beclabito Members of Wanakah Formation near Mesita, N. Mex. Massive Horse Mesa Member (about 150 ft thick) forms cliff. Beclabito Member of Wanakah Formation forms interbedded sequence in lower part of photograph. View is to the west.

Figure 6. Principal reference section of the Horse Mesa Member of the Wanakah Formation at Mesa Gigante. Horse Mesa Member is 155 ft thick. Kd, Dakota Sandstone; Jm, Morrison Formation; Jwh, Horse Mesa Member of Wanakah Formation; Jwb, Beclabito Member of Wanakah Formation; Jwt, Todilto Limestone Member of Wanakah Formation. View is to the north. Section shown is location 33 in figure 1; detailed location information in table 1.

marginal lacustrine depends on the interpretation of the Todilto as being marine or lacustrine. In either case, the Beclabito was deposited on low-lying areas marginal to a body of water.

Horse Mesa Member of the Wanakah Formation

The Horse Mesa Member of the Wanakah Formation is a sandstone at the top of the Wanakah in the Acoma sag area (fig. 1). The village of Mesita is near typical exposures of the unit. A principal reference section of the Horse Mesa Member is here established on the south side of Mesa Gigante, 6 mi east-northeast of Mesita, in SE¼NE¼sec. 12, T. 9 N., R. 4 W. In this area, the Horse Mesa almost everywhere forms a vertical cliff; one location that could be climbed and measured (fig. 6) serves as the reference section; a detailed description of the section is in the appendix.

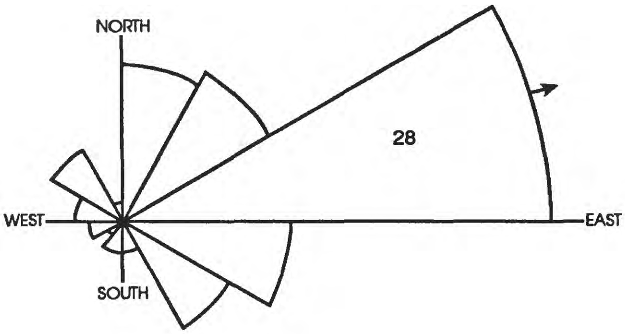
The Horse Mesa Member conformably overlies the Beclabito Member of the Wanakah Formation. In most of the exposures examined, the contact is gradational and is placed at the change from interbedded sandy siltstone and silty sandstone to massive sandstone. At one location (Crow Mesa, fig. 1) the contact is sharp and irregular.

At the reference section, the Horse Mesa is 155 ft thick, cliff-forming, reddish-brown, light-orange, yellowish-gray and white, very fine to coarse grained sandstone (fig. 6). The sandstone is moderately sorted, and grains are subangular to rounded. The Horse Mesa is mainly clean, quartzose sandstone, but coarse grains of white chert are a characteristic accessory mineral. At the reference section, the top of the Horse Mesa consists of about 10 ft of massive silty sandstone that contains irregular calcareous concretions. The thickness of the Horse Mesa ranges from 0 to 210 ft (fig. 1) and averages about 150 ft. The member is truncated by the overlying Dakota Sandstone in the southern part of the study area.

Bedding within the Horse Mesa Member is thin to very thick; sedimentary structures include subhorizontal, wavy, nonparallel laminations (flatbeds) interbedded with small to very large scale high-angle crossbed sets. The size and number of crossbed sets increases up section; individual laminae in the sets are inversely graded. Some flat-bedded sandstone strata exhibit dish structures and dissipation structures, which indicate fluid movement at the time of, or shortly after, deposition. The bases of both flatbed and crossbed sets commonly are loaded into underlying strata.

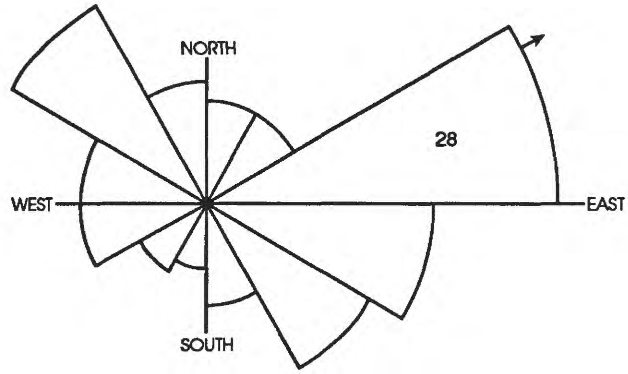
The Horse Mesa Member was deposited mainly in an eolian environment that included dunes and interdunes or sand sheets and some small fluvial channels. Eolian dunes are indicated by well-sorted sandstones that exhibit high-angle crossbeds, individual laminae of which are inversely graded. Crossbedding measurements indicate that eolian transport was generally to the northeast and southeast; the vector resultant from these studies indicates transport to the east-northeast (fig. 7).

Interdune or sand-sheet deposits are represented by numerous flatbedded sets. The flatbedded sets are bimodally sorted sandstone having irregular adhesion ripples, dissipation structures, and contorted beds, all of which are considered to be indicators of interdune



Vector resultant N. 73° E.
n=84
Spherical variance 0.0104

Figure 7. Rose diagram showing transport directions of the Horse Mesa Member of the Wanakah Formation in the San Juan basin. The number in the largest 30° arc segment is the number of readings within that segment. Other arc segments are drawn proportionately smaller.



Vector resultant N. 64° E.
n=143
Spherical variance 0.0146

Figure 8. Rose diagram showing transport directions of the Cow Springs Sandstone of the San Rafael Group in the San Juan basin. The number in the largest 30° arc segment is the number of readings within that segment. Other arc segments are drawn proportionately smaller.

deposits (Ahlbrandt and Fryberger, 1982, p. 31). The laterally extensive nature of both crossbedded and flat-bedded sets suggests that drier periods alternated with more moist periods over the entire area. The interdune or sand-sheet deposits commonly have stringers of coarse white chert grains, which may be lag deposits.

Near Dripping Springs (fig. 1), beds at the base of the Horse Mesa Member have features that indicate deposition in fluvial channels. These features include coarse to very coarse, poorly sorted sandstone, small- to medium-scale crossbeds, scoured bases, and abundant clay clasts. These small channels were not noted in areas to the north of Dripping Springs and may represent fluvial runoff from highlands to the south.

The Horse Mesa is considered to be a temporal equivalent of the upper part of the Cow Springs Sandstone because of its stratigraphic position above the Beclabito Member of the Wanakah. The Cow Springs is recognized as extending to just east of Thoreau (fig. 1); the Horse Mesa extends westward to about Thoreau. The original extent of the Horse Mesa to the northeast, east, and southeast of the Mesita area is unknown because of later erosion, which has removed the unit, or because the unit is deeply buried in the Rio Grande rift. The Horse Mesa Member is coarser grained than the Cow Springs Sandstone; this difference in grain size is interpreted to indicate slightly different source areas. The similarity of sedimentary structures of the two units, consisting of relatively thin but widespread, alternating crossbed and flatbed sets, indicates that they were deposited under similar conditions. Transport directions of the Cow Springs Sandstone are shown in figure 8 and indicate somewhat different source areas for the two units. Figure 8 also shows that there is more scatter in the crossbed readings of the Cow Springs, compared to those of the Horse Mesa.

The age of the Horse Mesa Member is Middle Jurassic based on its correlation with the Middle Jurassic Cow Springs Sandstone. No fossils were found in the Horse Mesa that would allow a more definitive age assignment. The Horse Mesa is considered to be part of the San Rafael Group, which consists of the Entrada Sandstone and the Wanakah Formation in the Acoma sag area.

Ongoing subsurface studies by the author and A.C. Huffman, Jr., suggest that the Horse Mesa Member of the Wanakah can be correlated from its type section throughout much of the San Juan basin. Figure 9 shows the nomenclature of Jurassic rocks on the northwestern, southwestern, south-central, and southeastern sides of the basin.

Eolian Facies of the Recapture Member of the Morrison Formation

Near Gallup, an eolian sandstone in the Recapture Member of the Morrison Formation overlies the Cow Springs Sandstone (Saucier, 1967; Adams and Saucier, 1981; Condon and Huffman, 1984; Condon, 1985b; Condon and Peterson, 1986). This sandstone is characterized by very large scale high-angle eolian crossbed sets that are interbedded with and grade laterally into flatbedded interdune deposits (fig. 10). In the Acoma sag, a sandstone displaying the same features overlies the Horse Mesa Member of the Wanakah (fig. 11). During this study, this sandstone was measured in detail at Mesa Gigante, South Butte, and Dripping Springs (fig. 1).

The sandstone above the Horse Mesa is yellowish gray, grayish red, and greenish gray, fine to medium grained, and well sorted. Grains are subangular to

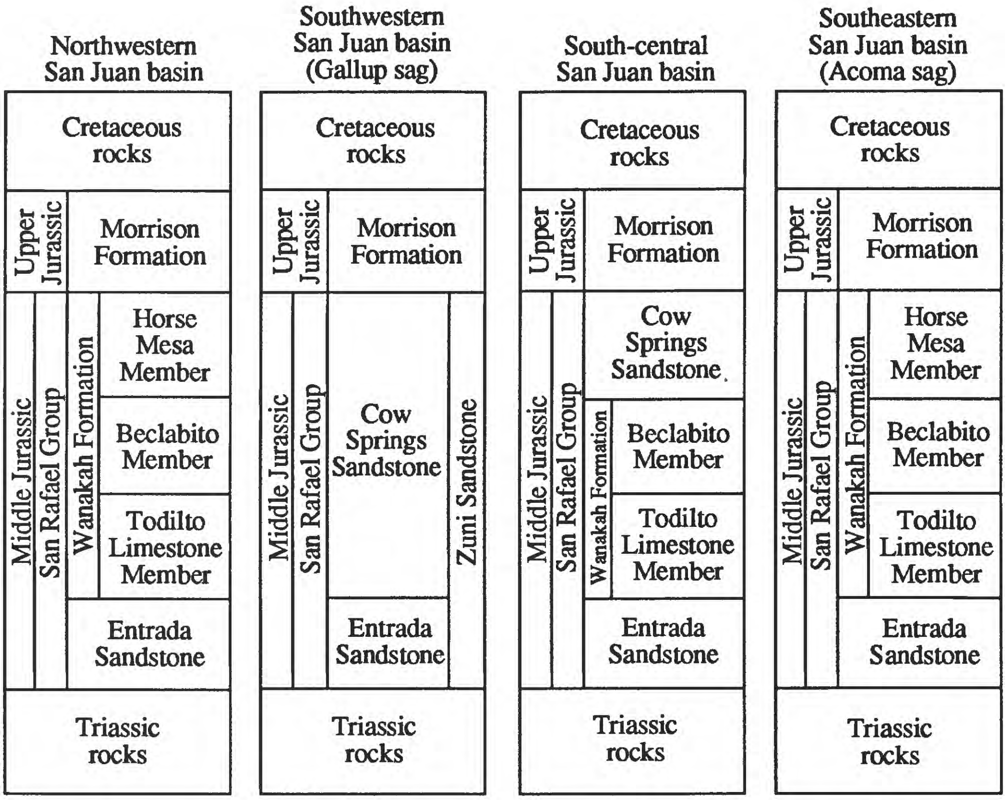


Figure 9. Jurassic nomenclature in the northwestern, southwestern, south-central, and southeastern San Juan basin, New Mexico. In the southern part of the Gallup sag, the Morrison Formation is absent, and the undifferentiated Cow Springs and Entrada Sandstones are called the Zuni Sandstone.

rounded. At the South Butte section (fig. 1), a few beds of dark-reddish-brown mudstone are present at the base and at the top of the unit. Bedding is thick to very thick, and sedimentary structures consist of very large scale high-angle crossbed sets and minor flatbedded intervals. In some areas, thick, massive intervals have no discernible sedimentary structures.

Large crossbed sets are the distinctive feature of this sandstone. Single set thicknesses of 60 ft, 115 ft, and 65 ft were measured at Mesa Gigante, South Butte, and Dripping Springs (fig. 1), respectively. Individual crossbed laminae are inversely graded; at South Butte, the laminae are from 0.5 to 6 in. thick. The laminae pinch out both parallel with and perpendicular to the dip of bedding and represent avalanche deposits or sand flows that developed on the lee slopes of eolian dunes (Ahlbrandt and Fryberger, 1982, p. 27). The transport direction of this eolian sandstone is to the northeast (fig. 12). Abrupt local facies changes from eolian dunes to interdunes distinguish this unit from the underlying Horse Mesa Member. In contrast, the Horse Mesa has thin, tabular, and widespread crossbedded and flatbedded strata.

The eolian sandstone is more than 210 ft thick at Mesa Gigante and thins to about 55 ft to the west-

Figure 10. Eolian facies of the Recapture Member of the Morrison Formation (Jmr) at Navajo Church, N. Mex. Spire of church is formed by the Westwater Canyon Member of the Morrison Formation (Jmw). Thickness from base of large-scale crossbed set to base of Westwater Canyon Member is approximately 160 ft. View is to the north.

southwest at The Narrows. The observed thinning is due to depositional thinning, erosion prior to deposition of the overlying Dakota Sandstone, or scour at the base of the Dakota. The sandstone is truncated southward in

Figure 11. Very large scale crossbeds in the eolian facies of the Recapture Member of the Morrison Formation at South Butte, N. Mex. Jacob staff (lower center) is 5 ft tall. View is to the south.

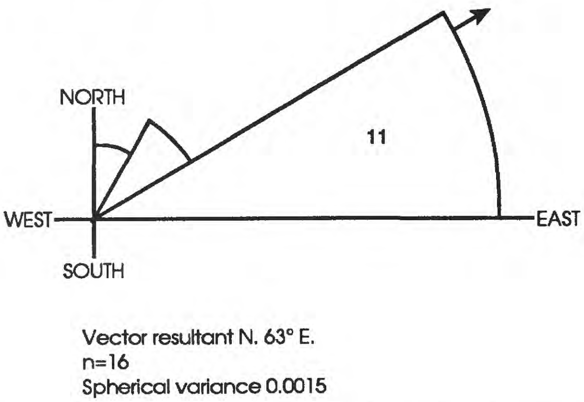


Figure 12. Rose diagram showing transport directions of the eolian facies of the Recapture Member of the Morrison Formation in the Acoma sag area. The number in the largest 30° arc segment is the number of readings within that segment. Other arc segments are drawn proportionately smaller.

outcrops on the east side of the Acoma sag between the Dripping Springs and Petaca Pinta sections (fig. 1).

The contact of the eolian sandstone beds of the Recapture with the underlying Horse Mesa Member is locally sharp but appears gradational at other places. This contact is important because it has been described as an unconformity in areas to the northwest of the San Juan basin (Pipiringos and O'Sullivan, 1978). At Mesa Gigante, a 10-ft-thick, silty sandstone at the top of the Horse Mesa Member is interpreted as a paleosol. This unit has many features considered characteristic of a paleosol, such as destruction of primary stratification, bioturbation and mottling, and carbonate nodules (Blodgett, 1988). It is overlain sharply by well-sorted, clean, eolian sandstone of the Recapture Member. In other areas, the lithology on either side of the contact is not as sharply defined, and the contact is placed at the base of the very large scale crossbed sets. The contact is also marked by a change in color from the common reds and browns of the Horse Mesa Member to the more pastel yellows and greens of the overlying eolian sandstone. With the exception of the Mesa Gigante section, the contact appears to be more gradational than unconformable in the Acoma sag area.

The contact between the eolian facies and the fluvial facies of the Recapture Member is conformable. In some places the eolian and fluvial strata are interbedded (Condon, 1985a, b). This interbedding of facies is most pronounced in the Lupton, Navajo Church, and Midget Mesa areas (fig. 1) (Condon and Peterson, 1986, p. 22) but has been observed as far east as Laguna (Huffman and others, 1984, p. 115) and Mesa Gigante (Moench and Schlee, 1967, p. 17). In the Acoma sag, the fluvial beds of the Recapture Member and the Westwater Canyon and Brushy Basin Members of the Morrison thin and pinch out depositionally and (or) were removed by pre-Dakota erosion in a southward direction.

The white sandstone member of Silver (1948), the upper part of the Bluff Sandstone of Moench and Schlee (1967), and the Zuni Sandstone of Maxwell (1976) are an eolian facies of the Recapture Member of the Morrison Formation. The Zuni Sandstone of Anderson (1983a) is an older unit, the top of which can be no younger than the Horse Mesa Member. The eolian sandstone is also present in the southwestern and southern parts of the San Juan basin, where it was called the white sandstone tongue of the Cow Springs Sandstone by Harshbarger and others (1957). Transport directions of the eolian sandstone of the Recapture in the south-central and southwestern parts of the basin, combined with readings taken in the Acoma sag, are shown in figure 13. Eolian beds in the Recapture have also been observed north of Lupton, along the western side of the San Juan basin, and northwest of Lupton in northeast Arizona, along the east side of Black Mesa.

The eolian sandstone of the Recapture Member is considered to be a temporal equivalent of the Bluff Sandstone Member of the Morrison Formation of Utah and of most of the Junction Creek Sandstone of southwest Colorado, although a physical connection has not been demonstrated. Each of these units is characterized by very large scale high angle eolian crossbeds that show consistent transport directions to the northeast.

SUMMARY

In the southeastern San Juan basin and Acoma sag, the lower and upper parts of the Bluff Sandstone of Moench and Schlee (1967) or the Bluff and Zuni Sandstones of Maxwell (1976) are composed of two distinct sandstone bodies that differ in color, grain size,

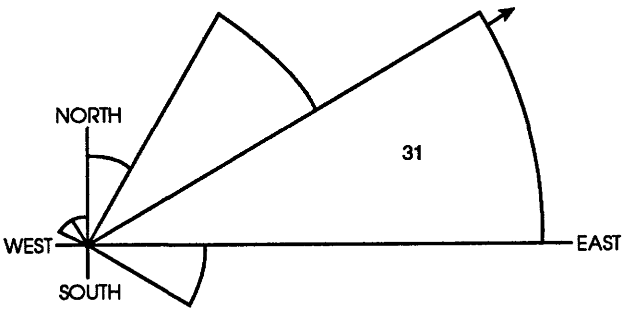


Figure 13. Rose diagram showing transport directions of the eolian facies of the Recapture Member of the Morrison Formation on the south side of the San Juan Basin, in the Gallup sag, and in the Acoma sag. The number in the largest 30° arc segment is the number of readings within that segment. Other arc segments are drawn proportionately smaller.

sorting, sedimentary structures, and facies distribution. The lower sandstone body is recognized as the Horse Mesa Member of the Wanakah Formation in this report, and the name Bluff Sandstone is no longer used. The upper sandstone body is recognized as part of the Recapture Member of the Morrison Formation and is equivalent to similar beds in the Recapture west of the Acoma sag; the name Zuni Sandstone is no longer used.

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APPENDIX

Appendix. Description of the principal reference section of the Horse Mesa Member of the Wanakah Formation in the southeastern San Juan basin

Location

Mesa Gigante (fig. 1, location 33), sec. 12, T. 9 N., R. 4 W., Mesa Gigante 7.5' quadrangle, Cibola County, New Mexico

Explanation of section form

The reference section of the Horse Mesa Member of the Wanakah Formation was recorded onto standardized forms that are reproduced here. The forms are divided into vertical columns that contain different types of information. Each column is explained briefly below.

Thickness/sample no.—This column is used to indicate thickness of the measured units, in feet.

Unit no.—This column is used to number depositional units. The units are not numbered in this section.

Fm/mbr.—Formation and member names are shown in this column.

Radioact./CPS.—CPS refers to counts per second of a handheld scintillometer. This column is not used in this section.

Visual porosity estimate—This column shows a continuous line graph that represents an estimate of the porosity of the measured unit. Estimates were obtained by placing a few drops of water or dilute HCl on the rock.

Core—This indicates the number of the core run for subsurface studies. It is not used in this section.

Rock type--This column shows a weathering profile of the outcrop, a lithologic symbol for rock type (symbols explained below), and sketches of sedimentary structures within the units.

Footnotes/color—Both of these columns indicate color of the units. Colors were estimated by a comparison with the Geological Society of America rock-color chart (Goddard and others, 1948). Where possible, colors were estimated from fresh, dry outcrops.

Dominant grain size—This column shows a continuous line chart of the dominant grain size of the measured unit. Grain size was estimated by a comparison to a standard grain size chart. Class divisions correspond to the phi scale. Dots to the left or right of the solid line indicate variations from the norm. V, very; Fn, fine; Sd, sand; Med, medium; Cse, coarse; Pbl, pebble.

Bedding—Bedding refers to set thickness of sedimentary units. VTK, very thick; TK, thick; MED, medium; TN, thin; VTN, very thin; MASS, massive.

Sedimentary structures—This column indicates the type of sedimentary structure that is shown graphically in the rock type column. CLL, curved, parallel laminations (trough or wedge-planar crossbeds); TAB. PLANAR, tabular-planar crossbeds; WII, wavy lamination (flatbedding); ELL, even, parallel laminations (horizontal laminations); STRLESS, structureless.

Biology/organics—This column indicates the presence of organic material, burrows, or bioturbation.

Sorting/roundness—Sorting: VWS, very well sorted; WS, well sorted; MWS, moderately well sorted; FS, fairly well sorted. Roundness: A, angular; SA, subangular; SR, subrounded; R, rounded.

Cement—This column indicates the presence of calcite cement. VC, very calcareous; MC, moderately calcareous; SC, slightly calcareous; NC, noncalcareous.

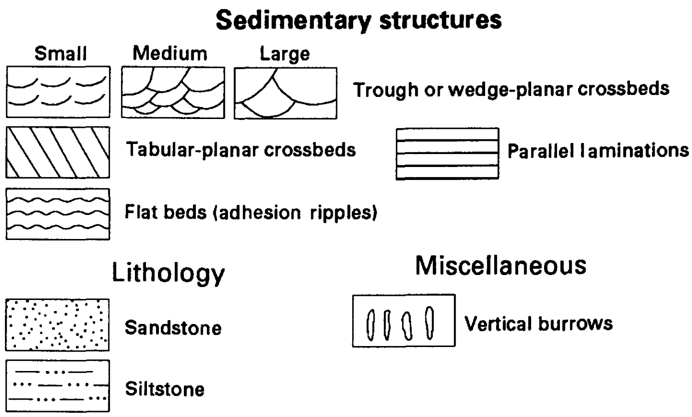
Percent feldspar—Estimated percent feldspar in the measured unit.

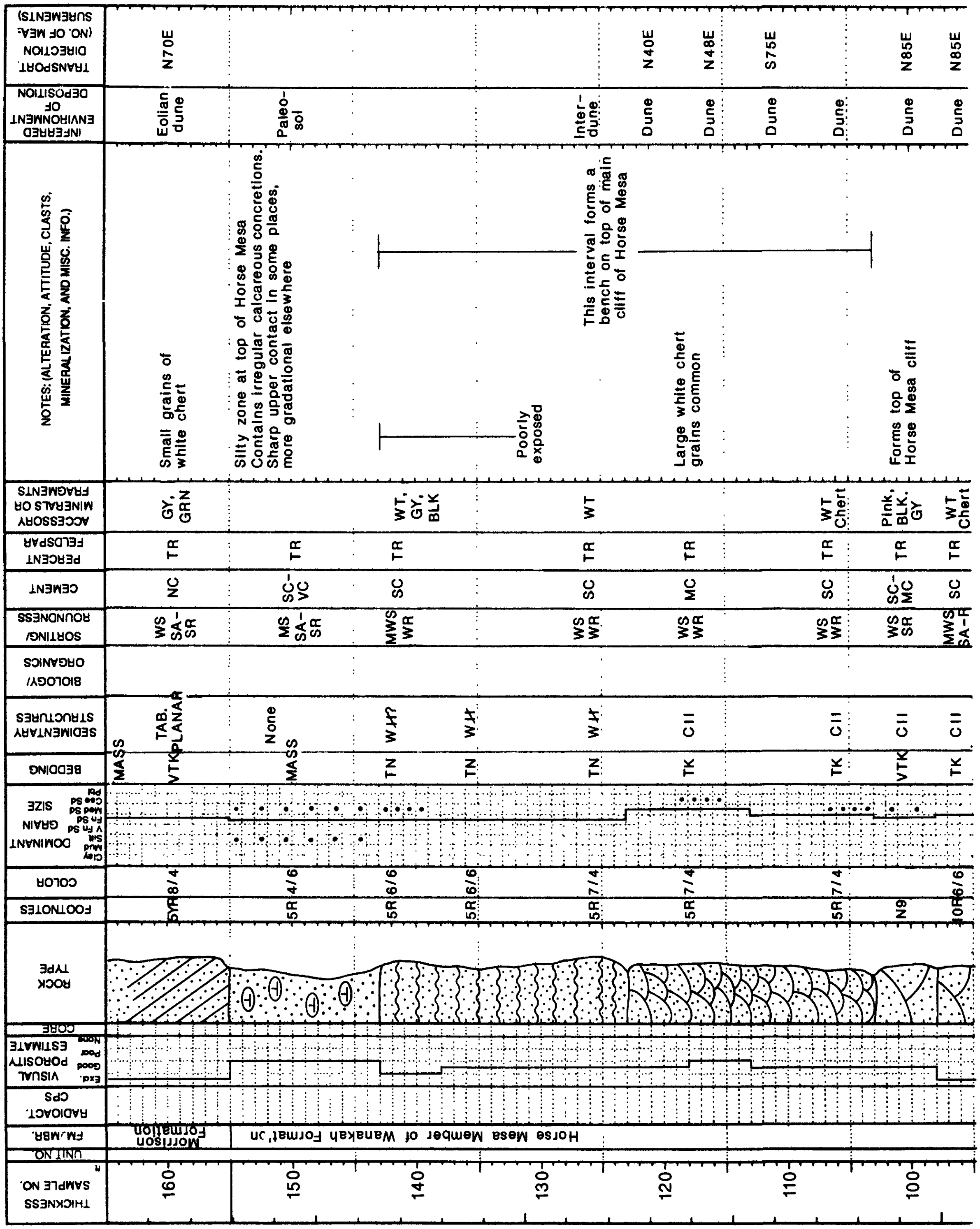
Accessory minerals or fragments--Colors of unidentified accessory minerals or rock fragments: BLK, black; GRN, green; GY, gray; WHT, white.

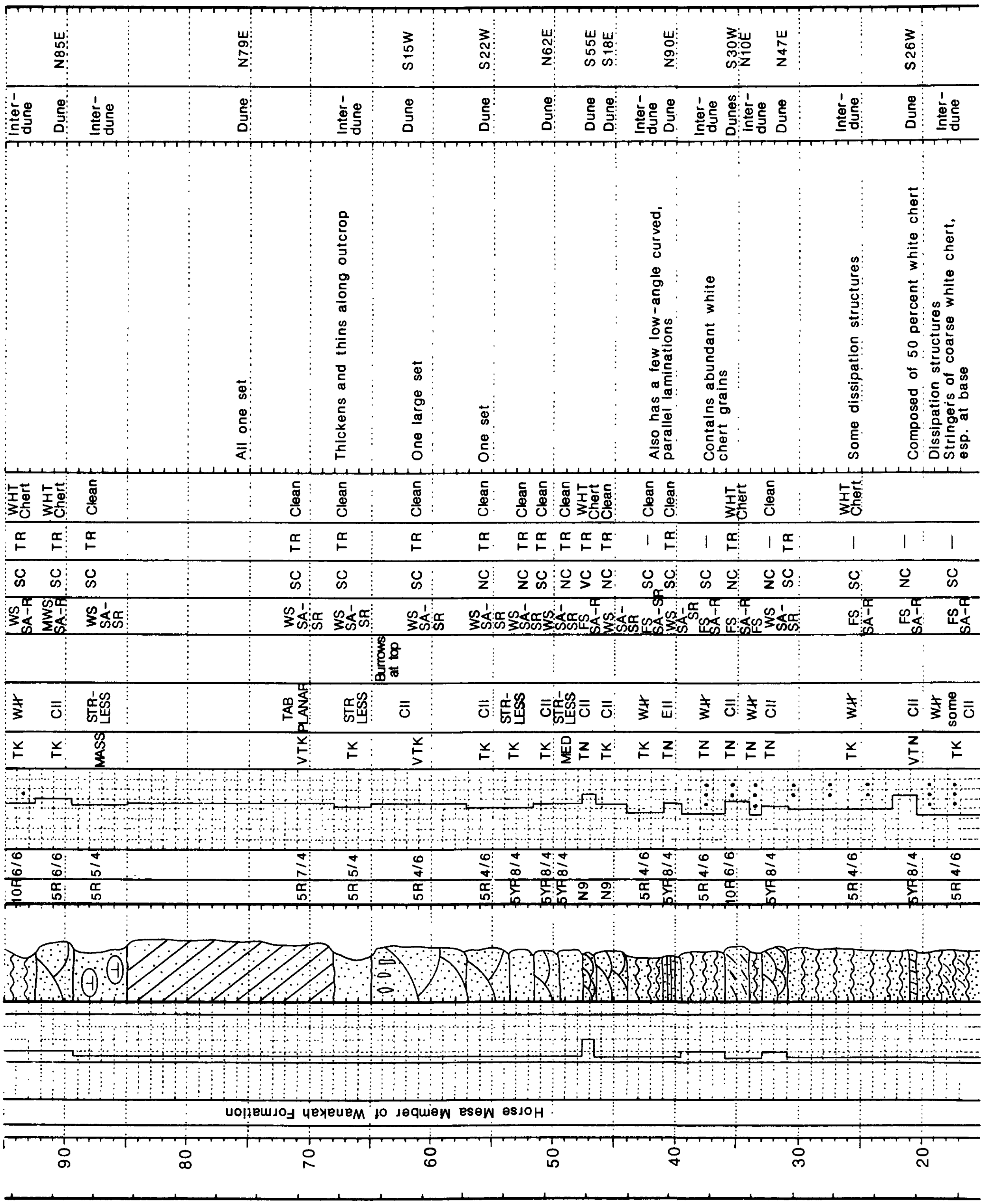
Notes—This comments section contains miscellaneous information not included anywhere else.

Inferred environment of deposition--Interpreted environment of deposition of the rock unit is shown in this column.

Transport direction—Estimates of the direction of sediment transport were made where possible. Most of these estimates are from axes of trough crossbeds or from tabular-planar crossbeds.

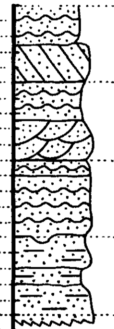



THICKNESS SAMPLE NO.
UNIT NO.
FM./MBR.
RADIOACT. CPS
VISUAL POROSITY ESTIMATE
CORE
ROCK TYPE
FOOTNOTES
COLOR
DOMINANT GRAIN SIZE
BEDDING
SEDIMENTARY STRUCTURES
BIOLOGY/ORGANICS
SORTING/ROUNDNESS
CEMENT
PERCENT FELDSPAR
ACCESSORY MINERALS OR FRAGMENTS
NOTES: (ALTERATION, ATTITUDE, CLASTS, MINERALIZATION, AND MISC. INFO.)
INFERRED ENVIRONMENT OF DEPOSITION
TRANSPORT DIRECTION (NO. OF MEASUREMENTS)
160
150
140
130
120
110
100
Morrison Formation
Horse Mesa Member of Wanakah Formation
5YR 8/4
5R 4/6
5R 6/6
5R 6/6
5R 7/4
5R 7/4
5R 7/4
N9
10R 6/6
MASS
VTK
MASS
TN
TN
TN
TK
TK
VTK
TK
TAB. PLANAR
None
CII
CII
CII
CII
WS SA-SR
MS SA-SR
MWS WR
WS WR
WS WR
WS WR
WS SR
MWS SA-R
NC
SC-VC
SC
SC
MC
SC
SC-MC
SC
TR
GY, GRN
WT, GY, BLK
WT
WT Chert
Pink, BLK, GY
WT Chert
Small grains of white chert
Silty zone at top of Horse Mesa
Contains irregular calcareous concretions.
Sharp upper contact in some places, more gradational elsewhere
Poorly exposed
This interval forms a bench on top of main cliff of Horse Mesa
Large white chert grains common
Forms top of Horse Mesa cliff
Eolian dune
Paleo-sol
Inter-dune
Dune
N70E
N40E
N48E
S75E
N85E
N85E



Horse Mesa Member of Wanakah Formation
90
80
70
60
50
40
30
20
All one set
Thickens and thins along outcrop
One large set
One set
Also has a few low-angle curved, parallel laminations
Contains abundant white chert grains
Some dissipation structures
Composed of 50 percent white chert
Dissipation structures
Stringers of coarse white chert, esp. at base
Burrows at top
Inter-dune
Dune
Dunes
N85E
N79E
S15W
S22W
N62E
S55E
S18E
N90E
S30W
N10E
N47E
S26W

Unit	Color		Thickness	Structures		Texture				Remarks	Environment	Paleocurrent
Horse Mesa Member	5YR	8/4	TK	TAB. PLANAR		MWS SA-SR	NC	TR	WHT Chert	One set	Dune	N85E
	5R	4/6	TK	WLr		FS SA-R	NC	—		Abundant coarse white chert	Inter-dune	
	5YR	8/4	TK	CII		FS SA-SR	NC	TR	WHT Chert	Inverse grading	Dune	S82E S65W
	10R	6/6	VTN	CII, WLr		FS, R	NC	—		Abundant white chert		S37W N85E
	5R	4/6	TK	WLr		FS SA-R	SC	—	WHT Chert	Base loaded into underlying unit; contact conformable	Inter-dune	
Beclabito Member of Wanakah Formation (incomplete)	5R and N8	3/4	TN	WLr		WS SA	VC	—	—	Weathers to hoodoos	Sabkha	



Chapter F

Eolian and Noneolian Facies of the Lower Permian Cedar Mesa Sandstone Member of the Cutler Formation, Southeastern Utah

By JOHN D. STANESCO and JOHN A. CAMPBELL

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1808

EVOLUTION OF SEDIMENTARY BASINS—SAN JUAN BASIN

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- Sandsheet facies F6
- Paleosols F6

Noneolian facies F8
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14. Map showing paleogeography of southeastern Utah during deposition of Cedar Mesa Sandstone Member F12

CONVERSION FACTORS FOR SOME SI METRIC AND U.S. UNITS OF MEASURE

To convert from	To	Multiply by
Feet (ft)	Meters (m)	0.3048
Miles (mi)	Kilometers (km)	1.609
Pounds (lb)	Kilograms (kg)	0.4536
Degrees Fahrenheit (°F)	Degrees Celsius (°C)	Temp °C=(temp °F–32)/1.8

Eolian and Noneolian Facies of the Lower Permian Cedar Mesa Sandstone Member of the Cutler Formation, Southeastern Utah

By John D. Stanesco[1] *and* John A. Campbell[2]

Abstract

Interpretation of lithologies, sedimentary structures, and isotope values in the Lower Permian Cedar Mesa Sandstone Member of the Cutler Formation suggests that the unit was deposited as a complex eolian system bordered to the east by fluvial environments (Cutler Formation), to the southeast by sabkha environments (Cedar Mesa Sandstone Member of the Cutler Formation), and to the north and west by marine environments (Rico Formation). The eolian part of the Cedar Mesa contains three genetic facies: dune, interdune, and sandsheet. The dune facies is characterized by wedge-planar and tabular-planar cross-strata that dip uniformly to the southeast, high-index ripple marks oriented parallel with foreset surfaces, inversely graded wind-ripple strata, lobate sand-avalanche strata, and wet-sand deformation structures. The interdune facies, by contrast, consists of horizontally bedded, thin, discontinuous layers of cherty limestone and siltstone. Mudcracks, sandstone dikes, and gypsum casts suggest alternating wet and dry conditions during deposition. The sandsheet facies consists of inversely graded wind-ripple strata that are horizontally bedded and commonly coated with coarse-sand lag grains.

The eolian facies of the Cedar Mesa interfinger with sediments deposited in three distinct noneolian environments around the perimeter of the dune field. Along the northeastern edge of the dune field, eolian sandstones are interbedded with fluvial rocks of the undifferentiated Cutler, which consist of arkosic sandstone and conglomerate. Terrestrial plant and animal fossils occur in overbank shales associated with stream channel deposits. To the southeast, near Bluff, Utah, eolian sandstones intertongue with thick deposits of silty gypsum and limestone of the Cedar Mesa. Sulfur and carbon isotope values suggest that these rocks originated in an environment characterized by mixed fresh and marine waters, possibly a coastal sabkha. The presence of a marine environment northwest of the dune field is suggested by an increase of sand-size marine fossil fragments in the dunes.

Numerous rhizoliths in the Cedar Mesa mark surfaces of stabilization and immature soil development within the dune field. These surfaces are associated with laterally extensive bedding planes that can be traced for more than 200 km. The surfaces rise stratigraphically in a downwind direction and probably resulted from migration of climbing eolian bedforms.

Paleogeographic interpretation suggests that sands of the Cedar Mesa were deposited as barchanoid or transverse dunes that migrated toward the southeast and terminated in a coastal sabkha. The sand originated in a marine environment to the northwest and a fluvial environment to the northeast. The location of these environments was controlled by two positive elements, the ancestral Uncompahgre uplift to the east and the Monument upwarp to the west.

INTRODUCTION

The Cedar Mesa Sandstone Member of the Cutler Formation is one of several dominantly cross-stratified quartzose sandstones of Early Permian or Wolfcampian age in the northern Colorado Plateau (fig. 1). These sandstones have been interpreted as marine in origin by some workers and as terrestrial in origin by others

[1]U.S. Geological Survey, Denver Federal Center, MS939, Denver, CO 80225, and Red Rocks Community College, Lakewood, CO 80401.

[2]Department of Geology, Fort Lewis College, Durango, CO 81301.

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(Baars, 1962; Loope, 1984a). Sedimentary structures, petrography, and isotope compositions for rocks from 13 measured sections of the Cedar Mesa in southeastern Utah were studied in an attempt to clarify paleogeographic interpretations (fig. 1).

The Cedar Mesa exhibits conformable relationships with both the underlying Rico Formation and the overlying Organ Rock Shale Member of the Cutler (fig. 2). Laterally, it interfingers with red beds of undifferentiated Cutler to the east; to the west, it disappears into the subsurface, merging lithologically with the Rico Formation or Elephant Canyon Formation and with the White Rim Member of the Cutler (D.L. Baars, Kansas Geological Survey, oral commun., 1985). South of the Arch Canyon section (fig. 1), the Cedar Mesa Member conformably overlies the Halgaito Member of the Cutler Formation (fig. 2).

The Cedar Mesa Sandstone Member crops out along the axis of the Monument upwarp in southeastern Utah (fig. 1), where it forms the fins and spires of the Needles District in Canyonlands National Park and the prominent upper cliffs in the canyons of the San Juan and Colorado Rivers above Lake Powell. It reaches its maximum outcrop thickness on the east side of the Monument upwarp (fig. 3), which was most likely an active structure during the Permian (Baars, 1962). The principal structural element influencing southeastern Utah during at the Permian was the ancestral Uncompahgre uplift, a mountain range to the northeast of the Cedar Mesa depocenter comprised of Precambrian granitic and metamorphic rocks (fig. 1).

We interpret the Cedar Mesa Sandstone Member as an eolian deposit having marine influences in both upwind and downwind directions. In the Cedar Mesa we

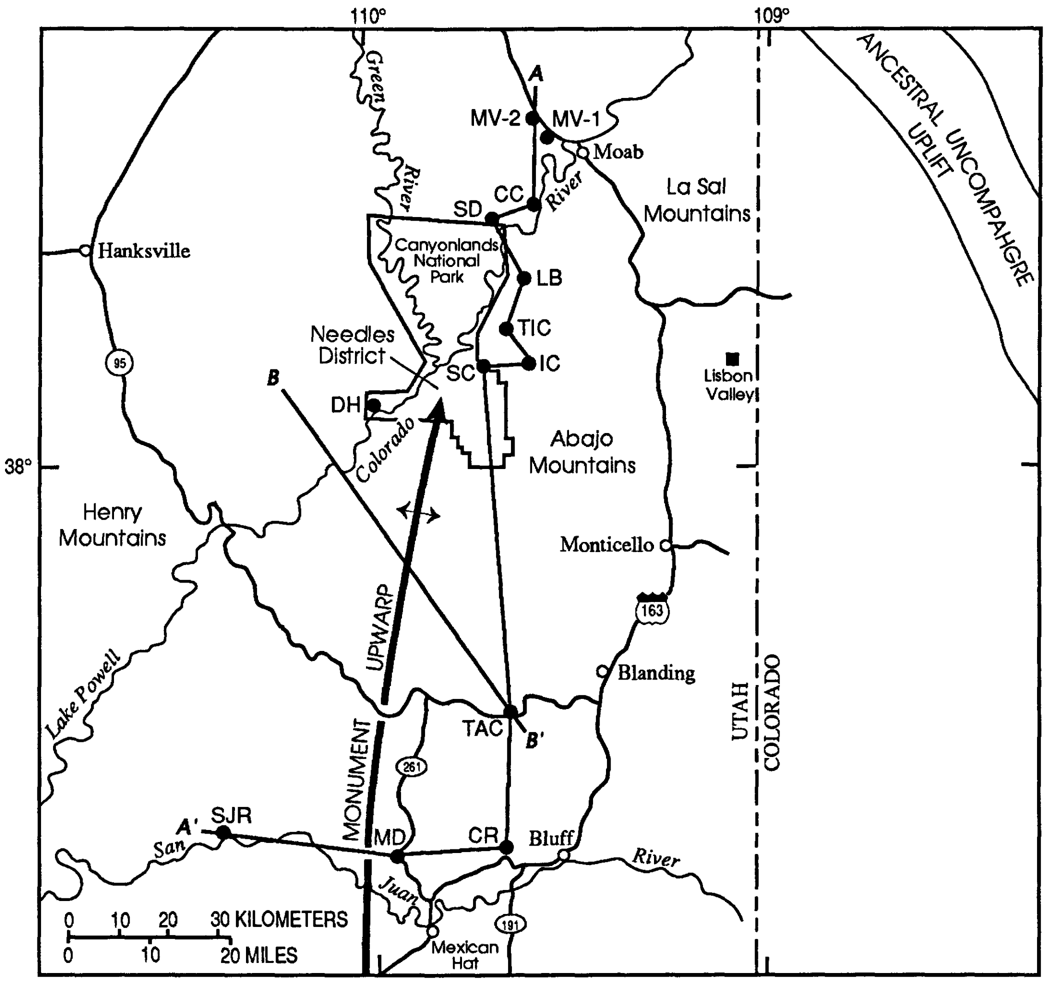


Figure 1. Location of measured sections used in study, southeastern Utah. MV–1 and MV–2, Moab Valley ; CC, Cane Creek; SD, Shafer Dome; LB, Lockhart Basin; TIC, tributary of Indian Creek; IC, Indian Creek; SC, Salt Creek; DH, Doll's House; TAC, tributary to Arch Canyon; CR, Comb Ridge; MD, Mokee Dugway; SJR, San Juan River. Lines of section *A* –*A'* and *B* –*B'* (fig. 9) are also shown.

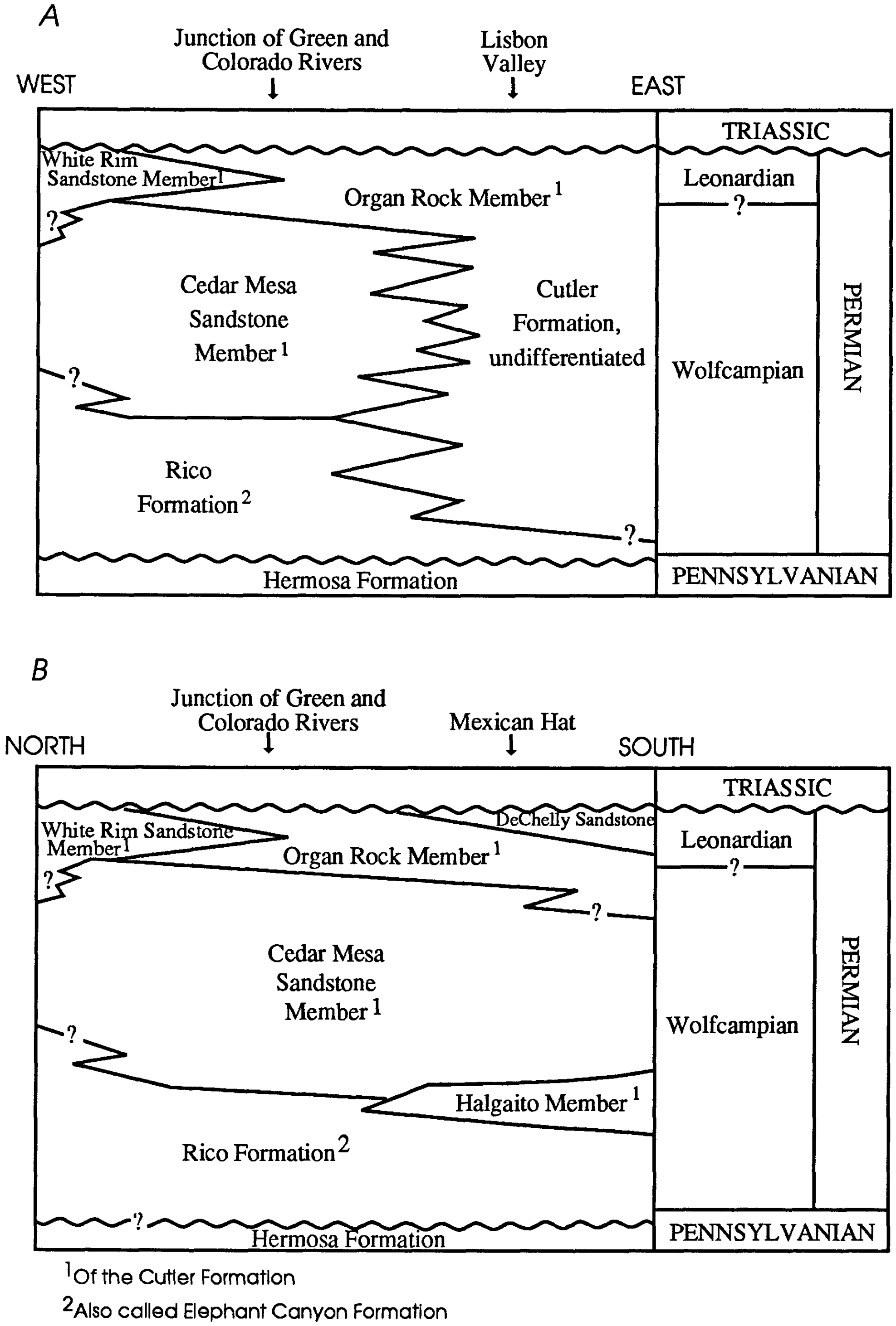


Figure 2. Schematic cross sections showing Permian stratigraphy of southeastern Utah. *A*, West-east. *B*, North-south. Modified from Baars (1962).

recognize three genetic eolian facies—dune, interdune and sandsheet (fig. 4*A*)—and we discuss the lateral relationships between these facies and three contemporaneous noneolian facies—fluvial, sabkha, and marine (fig. 4*B*). We also delineate possible large-scale structural controls on the location of these facies.

EOLIAN FACIES

Dunes

The dune facies of the Cedar Mesa Sandstone Member consists primarily of fine-grained quartzose

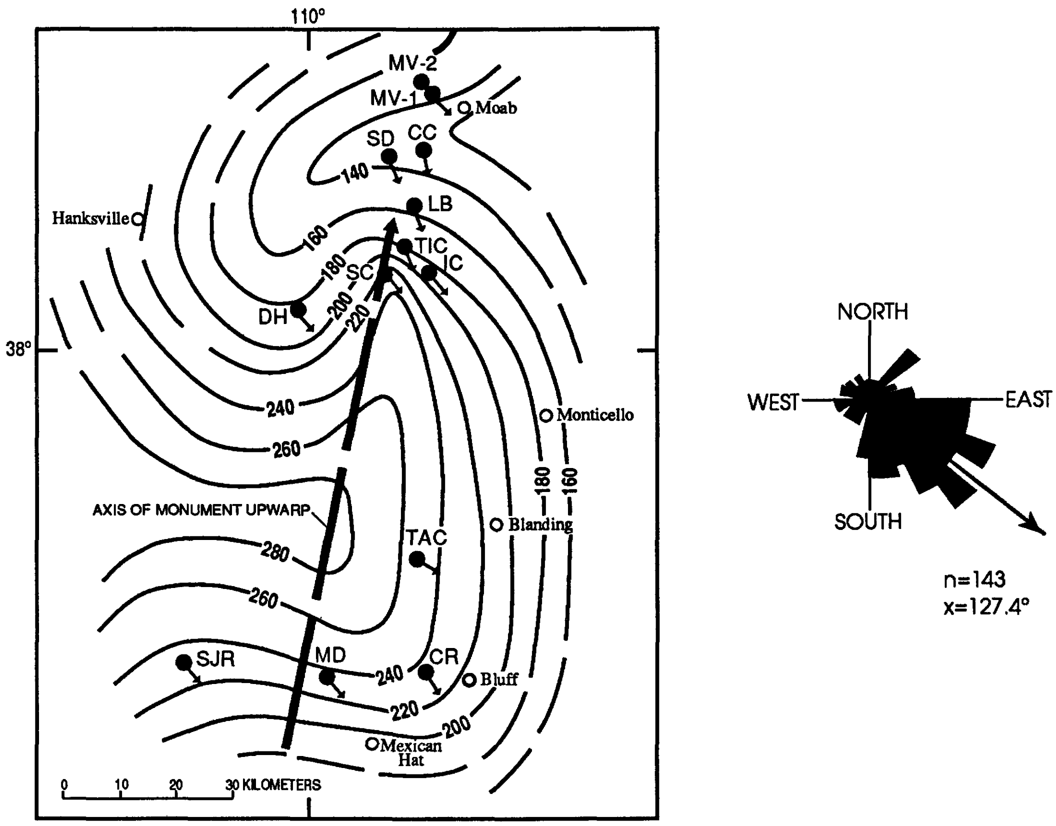


Figure 3. Outcrop isopach map of the Cedar Mesa Sandstone Member; contour interval 20 m. Mean crossbedding direction (arrow) at each measured section (solid circles, labels as in fig. 1) is shown. Rose diagram showing vector mean dip direction for all measured sections indicates inferred wind direction is to the southeast. Note that the Cedar Mesa thickens on the inferred downwind side of the Monument upwarp.

sandstone that contains some layers and lenses of medium- to coarse-grained sand. The most obvious characteristic of the dune facies is tabular-planar and wedge-planar crossbedding (fig. 5*A*), which occurs in sets from 0.1 to 15 m thick (average 1.4 m). Crossbedded strata constitute about 80 percent of the Cedar Mesa. Foresets dip almost exclusively to the southeast, with a mean direction of S. 37° E. (fig. 3*B*). The uniform dip direction suggests that the Cedar Mesa dunes were probably transverse or barchanoid ridge dunes (Blakey and Middleton, 1983) that were migrating to the southeast.

Although weathering has removed much of the detail from foreset surfaces, some traces of ripple marks oriented subparallel with the direction of dip are preserved. These high-index ripples probably formed as a result of wind eddies around the front of the dune and are considered good indicators of eolian deposition (Ahlbrandt and Fryberger, 1982).

Repetitive, inversely graded strata, each several millimeters thick, occur throughout the dune facies (fig. 5*B*). These were produced by the migration of wind-generated ripples (Hunter, 1977) along both topset layers and the lower part of foreset layers. In some of these strata, the ripple form can still be recognized. Several workers consider these laminae to be diagnostic of eolian deposition (Blakey and Middleton, 1983; Loope, 1984a).

Some cross section views of foreset beds show layers that are thicker and more poorly sorted than the wind-ripple strata discussed above. These layers are several centimeters thick and are commonly interfingered with wind-ripple strata near the base of foreset beds. They were probably produced by grain-flow sand avalanches down the slip faces of dunes. At the base of the slip faces, some avalanches formed sand-flow toes that are interfingered with wind-ripple strata along the basal dune apron (fig. 5*C*).

Contorted and convolute beds as thick as 3 m occur (fig. 5*D*) throughout the outcrop area of the Cedar Mesa Sandstone Member but are almost exclusively confined to foreset layers of the dune facies. Although most workers believe that this type of deformation occurs in water-saturated sand, its presence does not necessarily imply deposition in a subaqueous environment. Thompson (1969) argued that such structures result

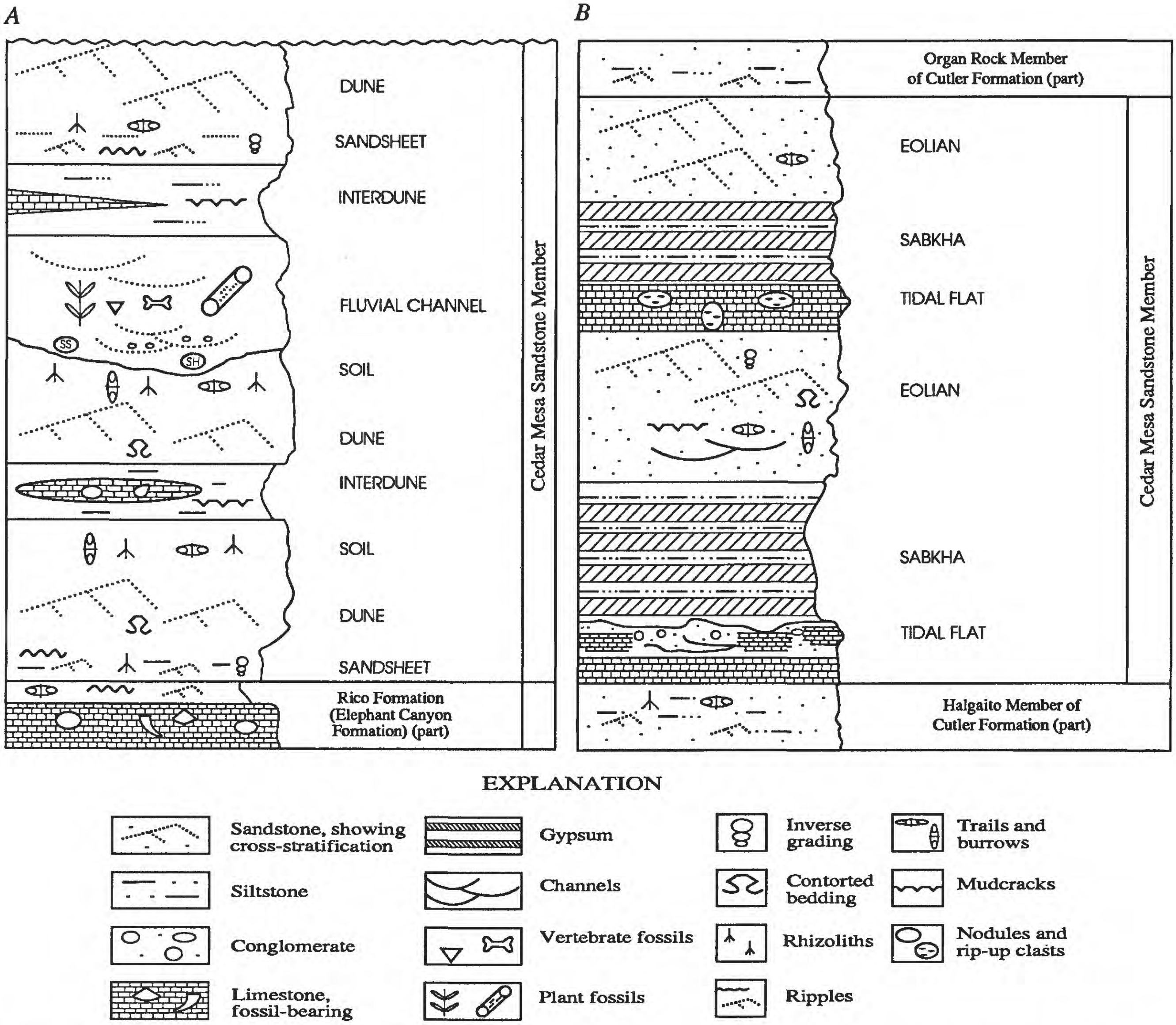


Figure 4. Schematic lithologic sections of the Cedar Mesa Sandstone Member. *A*, Canyonlands National Park. *B*, Comb Ridge area. The Rico Formation is also known as the Elephant Canyon Formation (Baars, 1962).

from the slumping of storm-wetted sand down the slip face of a subaerially exposed dune. Other workers (Doe and Dott, 1980; Horowitz, 1982) proposed that deformation occurs postdepositionally as the result of earthquake-induced liquifaction below the level of the water table. Neither explanation precludes an eolian origin for the convoluted sand layers, and several workers (Loope, 1981; Horowitz, 1982) attributed the restriction of these structures to foreset beds to the high porosity in grain-flow-produced strata.

Interdune Facies

Interdunes are topographically low areas between dunes. Some interdunes represent zones of scour and deflation, whereas others may be sites of wet or dry sediment accumulation (Ahlbrandt and Fryberger, 1982). Both the wet and dry interdune deposits may show evidence of bioturbation in the form of small burrows, trails, and root casts.

Wet interdune deposits in the Cedar Mesa Sandstone Member consist of thin, discontinuous cherty limestone, siltstone, and fine-grained sandstone. The limestone comprises irregular masses of sandy micrite commonly less than 0.5 m thick and pinches out laterally into horizontally bedded siltstone and fine-grained sandstone, which are themselves laterally discontinuous.

The wet interdune deposits probably formed in ephemeral ponds that were subsequently overridden by advancing dunes. The occasional drying out of these

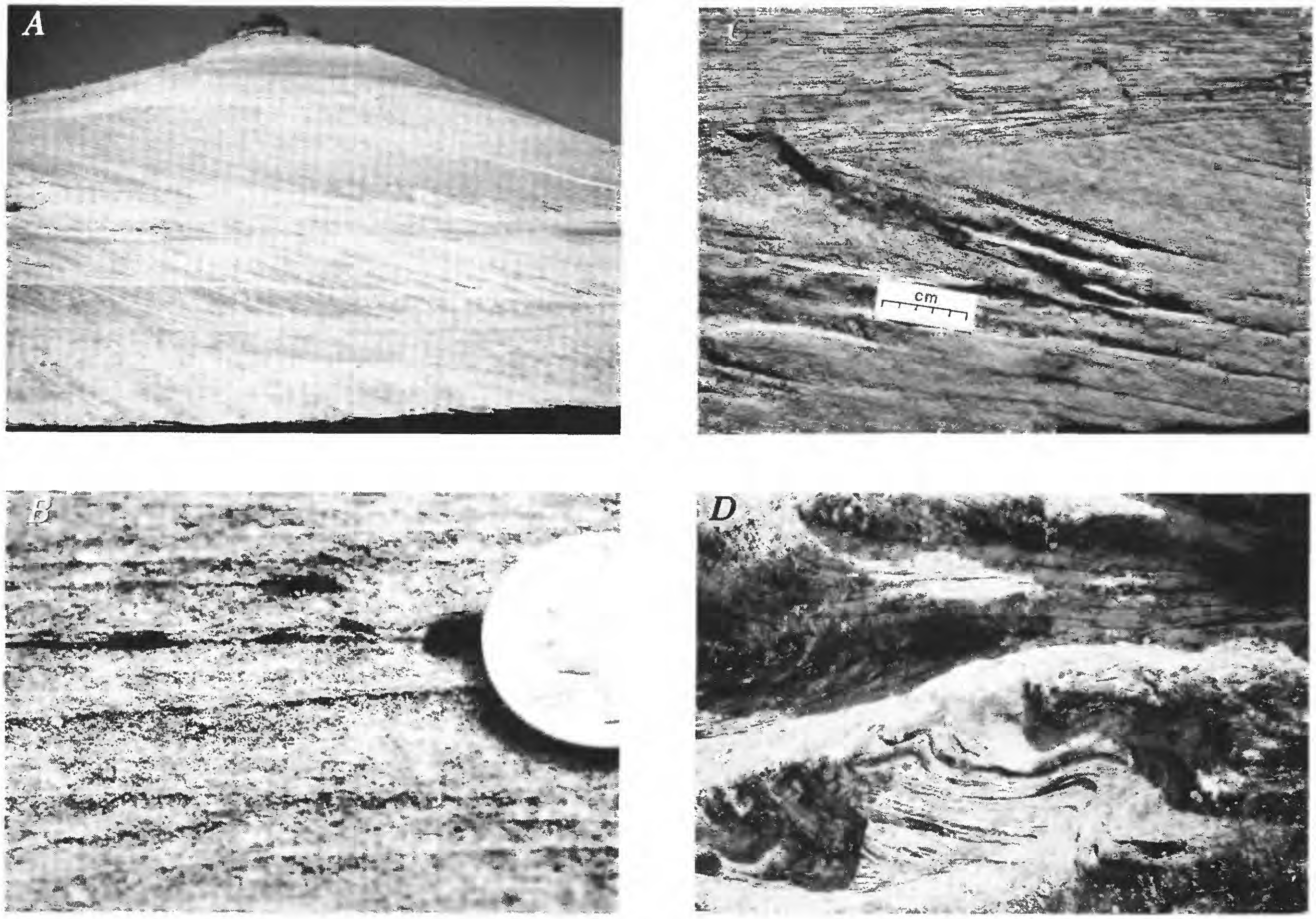


Figure 5. Characteristics of the dune facies of the Cedar Mesa Sandstone Member. See figure 1 for locations of sections. *A*, Tabular-planar and wedge-planar cross-sets showing uniform southeast dip; outcrop is about 15 m high. Northeast of Mokee Dugway section; view looking northeast. *B*, Inverse grading in wind-ripple laminations. Salt Creek section. *C*, Coarse-grained sand-avalanche deposits wedging into wind-ripple-laminated deposits. Indian Creek section. *D*, Convolute bedding of foreset layers; outcrop is about 4 m high. Arch Canyon section.

ponds is indicated by desiccation features including mudcracks and gypsum casts. Mudcrack polygons (fig. 6) 0.1–0.5 m in diameter and sandstone wedges commonly occur at the base of units that overlie the interdune siltstone. Similar structures noted in modern sabkha environments have been attributed to dessication in evaporitic muds (Glennie, 1970).

Dry interdune deposits in the Cedar Mesa Sandstone Member consist of horizontally stratified sandstone deposited by wind ripples.

Sandsheet Facies

The sandsheet facies consists of low-angle to horizontally stratified sandstone that probably was deposited in sandy plains within and around the Cedar Mesa dune field. Although sandsheet deposits resemble dry interdune deposits in terms of lithology and sedimentary structures, they generally have a greater lateral extent. Discontinuous, inversely graded wind-ripple laminations within horizontally stratified to massive sandstone are a primary characteristic of this facies (fig. 7). Medium to coarse sand grains commonly coat bedding surfaces composed of finer sand and are probably lag grains that were left behind as the wind blew away the finer material. Root casts, burrows and trails are common in this facies.

Paleosols

Numerous horizontal, massive, varicolored sandstones within the Cedar Mesa Sandstone Member (fig. 8*A*) are characterized by mottled coloring, a lack of stratification, and discontinuous zones of claystone and nodular limestone. These sandstones also exhibit bioturbation in the form of small, infilled burrows as long as 10 cm and a centimeter in diameter and limestone and

Figure 6. Mudcracks in wet interdune deposit infilled with sand of overlying eolian unit, Cedar Mesa Sandstone Member. Hammer shown for scale. Salt Creek section (fig. 1).

Figure 7. Horizontal to low-angle cross-stratification formed by wind-ripple laminations in the sandsheet facies of the Cedar Mesa Sandstone Member. Lens cap shown for scale. Salt Creek section (fig. 1).

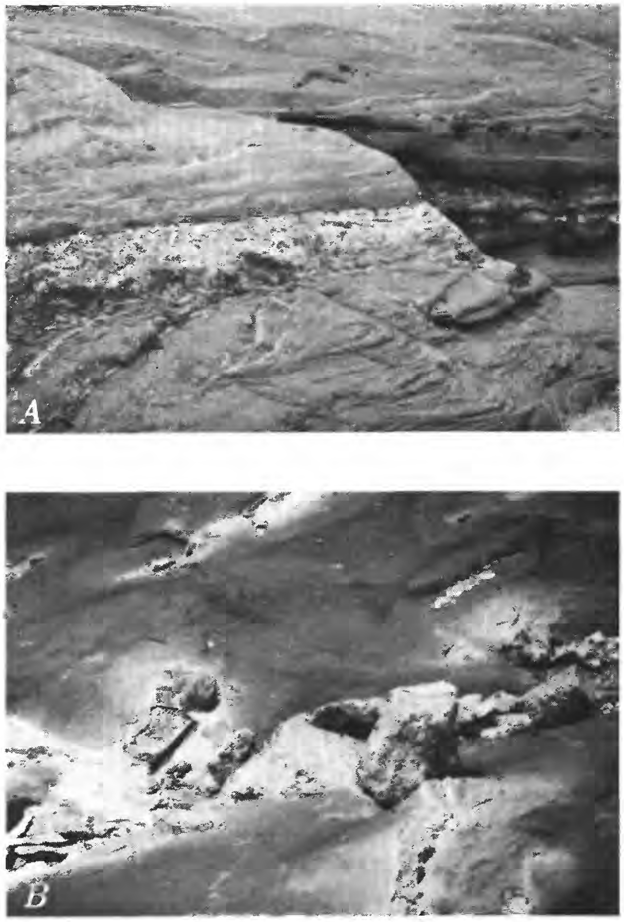


Figure 8. Characteristics of paleosols within the Cedar Mesa Member. Needles Distict, Canyonlands National Park (fig. 1). *A*, Laterally extensive, mottled sandstone (about 2 m thick) interpreted as a paleosol. *B*, Limestone cast of stump and radiating roots. Pen shown for scale (center left of photograph).

limonitic rhizoliths (Loope, 1981) as long as a meter and 20 cm in diameter. In several locations the rhizoliths radiate from vertical central cores that clearly resemble tree stumps (fig. 8*B*). These units have many of the characteristics of arid region paleosols (Retallack, 1983) but lack the distinctive soil horizons that indicate mature pedogenesis. They do represent, however, zones of stabilization and incipient soil development within the dune field.

The varicolored sandstones are interbedded laterally with rocks of the interdune and fluvial facies. Their upper and lower contacts are sometimes gradational but more commonly are abrupt and marked by horizontal bedding planes of great lateral extent (fig. 8*A*). Loope (1985) traced some of these bedding planes for several tens of kilometers, and we correlated bedding-plane surfaces for the length of outcrop exposure for the Cedar Mesa Sandstone Member, a distance of more than 200 km (fig. 9).

The origin of these bedding planes is controversial. Some workers (Kocurek, 1981; Rubin and Hunter, 1982) proposed that most laterally extensive surfaces in eolian systems result from the migration of climbing bedforms. Loope (1984b, 1985), on the other hand, suggested that the surfaces in the Cedar Mesa Sandstone Member are erosional and formed as a result of deflation down to the level of the water table, a model first proposed by Stokes (1968). Kocurek (1984) subsequently accepted Loope's model for the Cedar Mesa Sandstone Member with the condition that the erosional surfaces represent significant external events imposed on the dune field, events such as a marine transgression or a major change in wind regime. Rubin and Hunter (1984) illustrated how bounding surfaces associated with evaporites and paleosols can be formed by climbing dunes. Our correlation of these

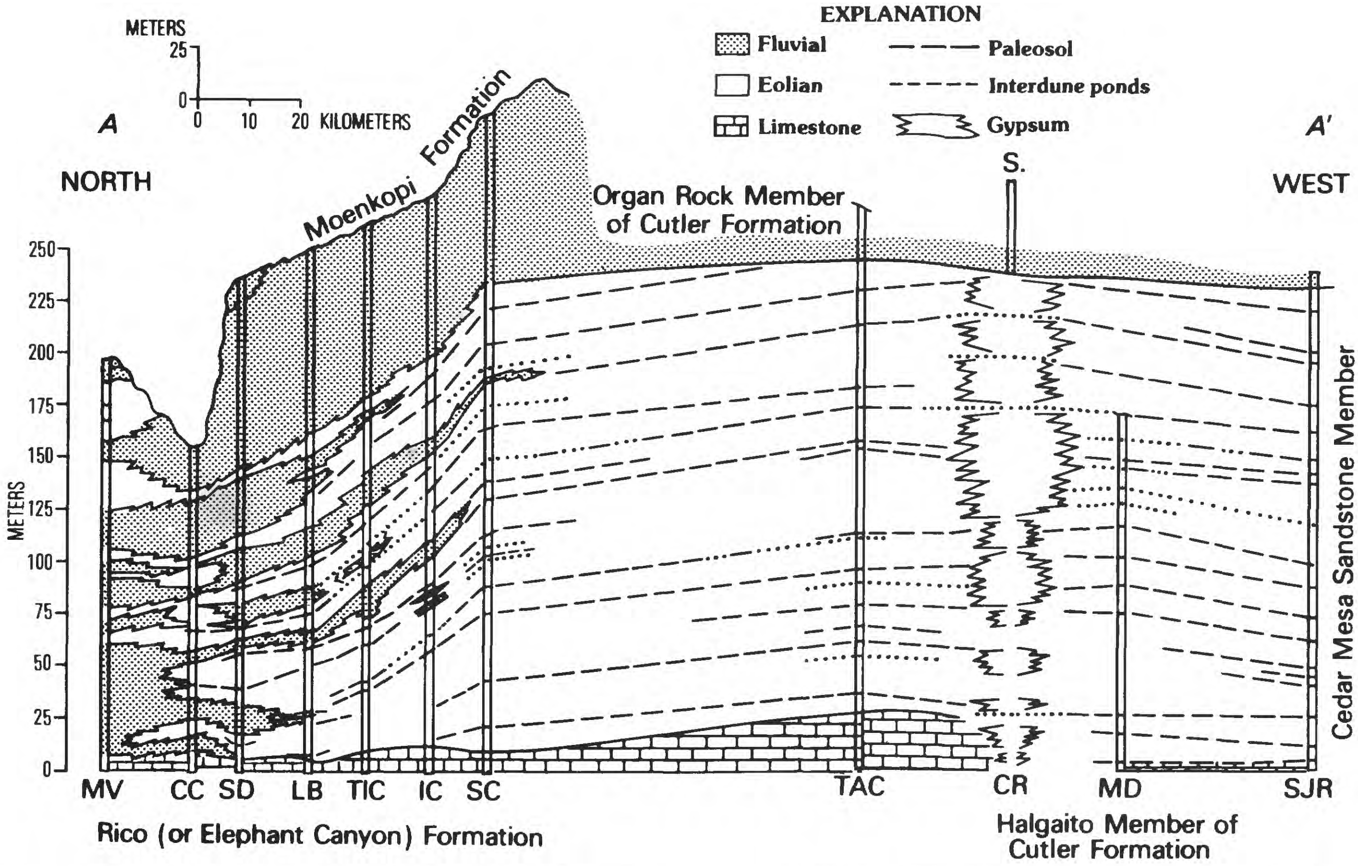


Figure 9 (above and facing page). Correlations along paleosols within the Cedar Mesa Sandstone Member of the Cutler Formation. *A*, North-south-west. *B*, Northwest-southeast. Lines of sections and locations of measured sections shown in figure 1.

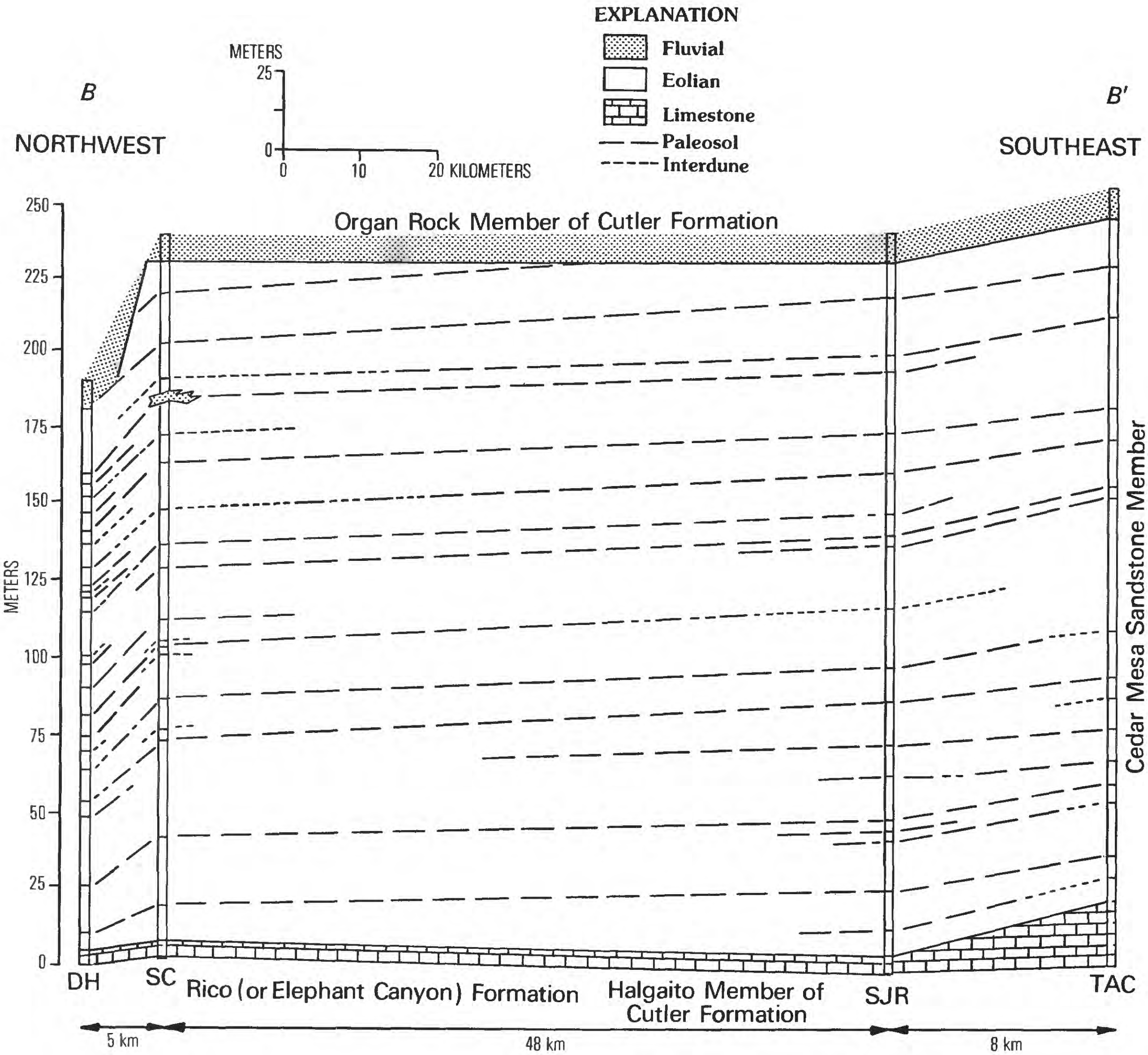
surfaces suggests that the paleosols and associated bedding planes rise stratigraphically in a downwind direction (fig. 9); thus, they migrated with adjacent eolian facies and resulted from climbing bedforms.

NONEOLIAN FACIES

Fluvial Facies

Along the northeast edge of the study area, arkosic sandstone and conglomerate and associated micaceous siltstone and shale interfinger with quartzose sandstone of the Cedar Mesa Sandstone Member. The arkosic rocks are in trough cross-stratified sheet sandstones as thick as 10 m (fig. 10*A*). Some of these sandstones intertongue with rocks of the eolian facies over distances of 8 km. Individual trough sets are 0.25–2.0 m thick and as wide as 8 m. Micaceous siltstone and shale adjacent to these troughs form horizontally bedded lenses and layers as wide as 20 m. We interpret all of these sediments to be channel and overbank deposits of streams that drained the ancestral Uncompahgre uplift. Paleocurrent measurements of trough cross-sets within the channels suggest that most of the streams flowed from northeast to southwest. The northwest paleocurrent trend in the northern part of the study area, however, reflects the deflection of streams around the nose of the Monument upwarp, which was most likely a positive structure during part of the Early Permian (Baars, 1962).

Some of the streams that flowed into the Cedar Mesa dune field fed interdune ponds. This relationship can be seen at the Indian Creek section (fig. 1), where trough cross-stratified arkosic sandstone interfingers with a discontinuous micritic limestone that is interpreted to be an interdune deposit. Several silicified conifer logs (fig. 10*B*), the largest of which is 8 m long and 1 m in diameter, are imbedded in the limestone. The logs are aligned normal to the current direction of the associated fluvial deposits as determined from paleocurrent analysis. Several reptile bones and teeth, including a jaw fragment of some type of pelycosaur (J.M. Parrish, University of Colorado Museum, oral commun., 1984), were also observed. Less than a kilometer away, in the same fluvial unit, impressions of plant stems and fern leaves occur in overbank shales. Some of the stem fragments belong to the genus *Equisituum* (horsetail



plants), and the fern leaves closely resemble *Astrotheca*, a common fern in the Permian of Gondwanaland (J.A. Townrow, Red Rocks Community College, oral commun., 1984). The fragmental nature of the impressions suggests that the plants were probably transported into the sediments. In the Needles District, fluvial units become thicker and more abundant toward the top of the Cedar Mesa until they predominate in the conformable, overlying Organ Rock Member.

Sabkha Facies

Sandstone near the southeastern limit of exposures of the Cedar Mesa Sandstone Member are interfingered with gypsum, siltstone, and limestone in a section 240 ft thick (fig. 11*A*). These lithologies continue south in the subsurface for approximately 125 km (Blakey, 1980; S.M. Condon, oral commun., 1986). The gypsum is massive to nodular and crops out in layers as thick as 10 m. It commonly interfingers with siltstone and locally forms thin stringers that cut across the bedding of adjacent silstone. Chert nodules occur within some of the gypsum beds.

Individual limestone beds are generally less than a meter thick. They are heavily bioturbated and exhibit desiccation features. Some are brecciated, and commonly contain flat-pebble conglomerates. Toward the top of the Cedar Mesa interval, possible stromatolitic structures occur locally in some of the limestones (fig. 11*C*).

In this zone of interfingering, the sandstones of the Cedar Mesa retain diagnostic eolian characteristics such as alternating sets of wind-ripple laminations and

Figure 10. Characteristics of the fluvial facies of the Cedar Mesa Sandstone Member. Indian Creek section (fig. 1). *A*, Fluvial channel consisting of arkosic sandstone and overbank micaceous siltstone cuts into and is overlain by eolian sandstone; outcrop is about 4 m high. *B*, Petrified coniferous log in fluvial channel deposit.

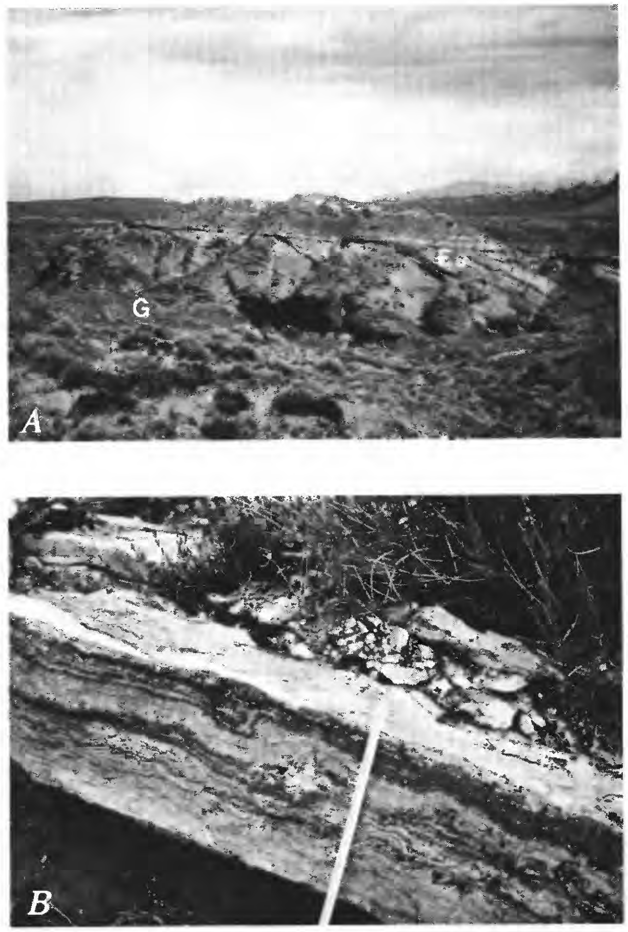


Figure 11. Characteristics of the sabkha facies of the Cedar Mesa Sandstone Member. See figure 1 for location of Comb Ridge section. *A*, Massive gypsum layers (G) interbedded with cross-stratified eolian sandstone (Es). Near Comb Ridge section. *B*, Possible algal stromatolitic structures in limestone bed. Comb Ridge section.

avalanche-produced features. The rhizoliths that characterize the Cedar Mesa farther to the north were not observed, but burrows and trails remain. Many of these features suggest that the Cedar Mesa dunes encroached upon and interfingered with sediments deposited in an ephemeral, evaporating body of water. Fluctuations in water level were common, and at times the sediments were subaerially exposed. This interpretation is supported by the presence of desiccation and brecciation features in the limestone and by the eolian character of the interbedded sandstone.

The above features are found both in inland sabkhas associated with playas and in coastal sabkhas adjacent to marine tidal flats (Glennie, 1970), but because the interfingering zone of the Cedar Mesa disappears into the subsurface, we were unable to determine from outcrop evidence which type of sabkha is represented. We therefore turned to geochemical analysis in an attempt to answer this question.

It has been demonstrated that for a given time interval the range of isotope values for sulfur of marine origin is narrow (Claypool and others, 1980). $\delta^{34}S$ values for gypsum samples of the Cedar Mesa at the Comb Ridge section (fig. 1) are within the range of normal marine sulfates for Wolfcampian time (fig. 12*A*) and therefore the evaporite units of the Cedar Mesa were most likely exposed to marine waters. Results of an evaluation of the carbon and oxygen isotope values for four limestones of the Cedar Mesa are less consistent (fig. 12*B*). Two of the four limestones have carbon and oxygen isotope values that are outside the range of common marine limestones (Hudson, 1977); these values may be the result of a mixing of marine and fresh water, and the oxygen isotope values may also indicate intense evaporation. Though not unequivocal, interpretation of the isotopic data suggests that the sabkha facies of the Cedar Mesa Member was fed at least in part by marine water.

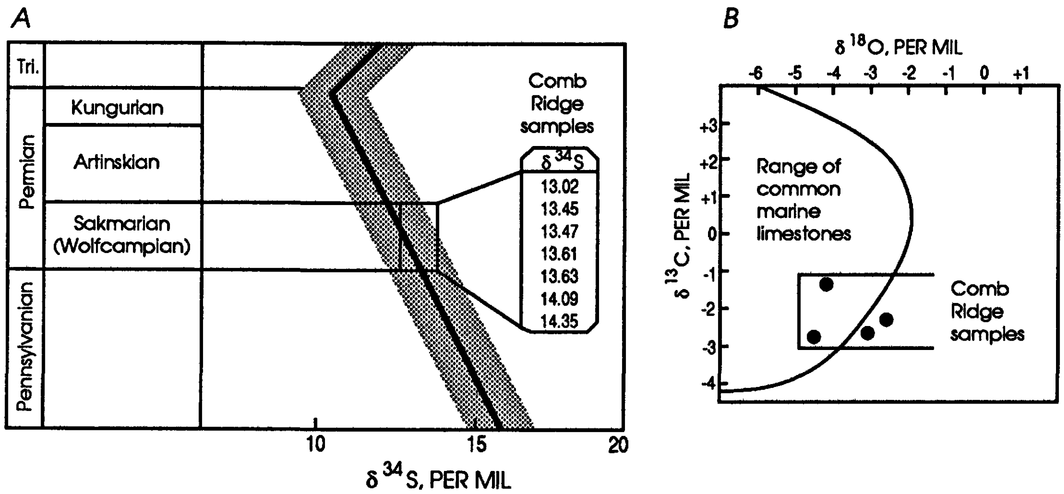


Figure 12. Isotope values for gypsum and limestone in samples of Cedar Mesa Sandstone Member. Comb Ridge section (fig. 1). *A*, Sulfur isotope values for gypsum. Range of normal marine sulfur isotope values for upper Paleozoic and Lower Triassic rocks (Claypool and others, 1980) is shown by screen pattern. Sulfur isotope values for Comb Ridge samples are all within range of normal marine sulfur for lowermost Permian (Wolfcampian). *B*, Carbon and oxygen isotope values for limestones. "Heavy" oxygen isotope values may be result of intense evaporation. Range of values for marine limestones from Hudson (1977). Analyses by Global Geochemistry Corporation, Canoga Park, Calif.

Marine Facies

The presence of a coeval marine environment to the north and west of the eolian facies of the Cedar Mesa Sandstone Member has been suggested by several workers (Baars, 1962; Loope, 1984a). Recent work (D.L. Baars, oral commun., 1985) on the subsurface geology west of Canyonlands National Park suggests that the Cedar Mesa Sandstone Member interfingers with marine carbonates of the Rico Formation (Elephant Canyon Formation of Baars, 1962).

Features such as wind-ripple strata and sand-avalanche toes in our westernmost measured section, the Doll's House section (fig. 1), indicate eolian deposition; however, the increase from east to west throughout the study area of wind-deposited, sand-size marine fossil fragments (fig. 13) and carbonate pellets suggests a nearby marine environment north and west of the dune field.

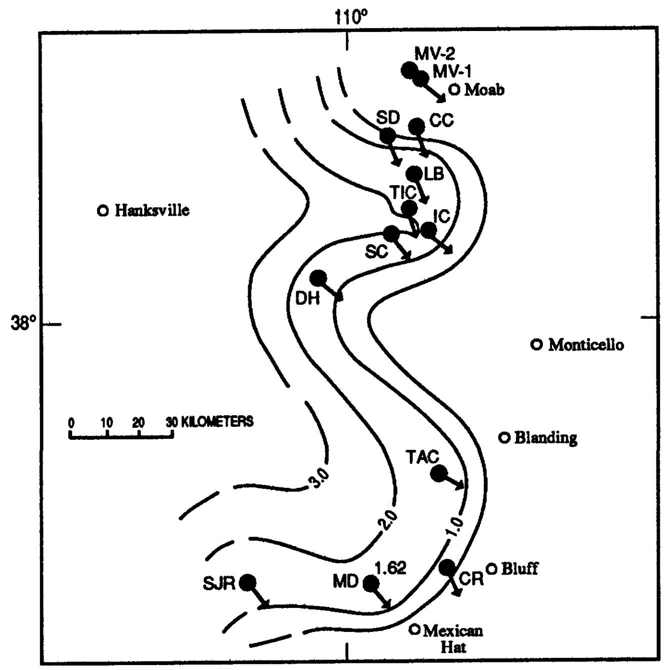


Figure 13. Contour map of fossil fragment content in the Cedar Mesa Sandstone Member; contour interval 1 percent. The westward increase in fossil fragments indicates a marine environment west of the depositional area of the Cedar Mesa Sandstone Member. Arrows show mean paleocurrent direction at locations of measured sections (solid circles, labels as in fig. 1).

CONCLUSIONS

Our study of the sedimentary environments that coexisted in southeastern Utah during deposition of the Lower Permian Cedar Mesa Sandstone Member of the Cutler Formation permits interpretation of the paleogeography during this interval (fig. 14). Most of the Cedar Mesa formed in an eolian depositional environment consisting of dunes, dry and wet interdunes, and sandsheets. The dunes were dominantly transverse or barchanoid ridges and migrated under winds directed consistently to the southeast. Dune migration terminated in a coastal sabkha that was fed, in part, by marine waters to the south.

A marine shoreline also existed upwind of the dune field and was probably the primary source of sand for the Cedar Mesa dunes; westward-flowing streams from the ancestral Uncompahgre uplift provided less significant amounts of sand. The streams flowed into the northeast edge of the dune field and occasionally produced interdune ponds. These wet areas supported both plant and animal life including large coniferous trees and tetrapod reptiles. Immature paleosols associated with almost horizontal bedding planes extend throughout the outcrop exposure of the Cedar Mesa. Correlation of these surfaces indicates that they rise stratigraphically in a downwind direction, probably as a result of the migration of eolian bedforms.

Two tectonic elements structurally controlled the location of depositional environments in the Cedar Mesa Sandstone Member. The ancestral Uncompahgre uplift to the east provided a source of clastic debris for the Cedar Mesa dunes and formed a major structural barrier that confined the genetic facies to the western flank of the uplift. The Monument upwarp to the west also influenced the development of the Cedar Mesa dune field.

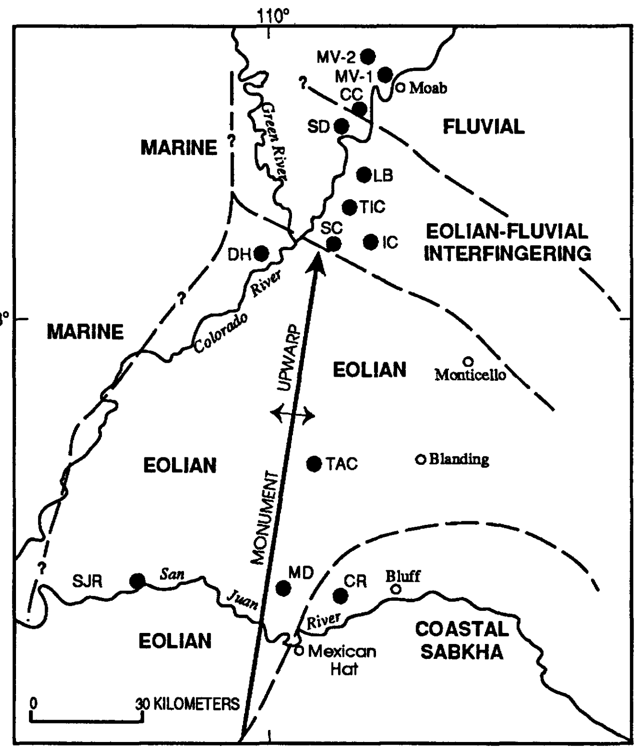


Figure 14. Paleogeography of southeastern Utah during deposition of the Cedar Mesa Sandstone Member. Locations of measured sections (solid circles, labels as in fig. 1) are shown for reference.

Isopachs of the outcropping Cedar Mesa indicate that the eolian facies gain their maximum thickness just to the lee of the axis of the Monument upwarp. The upwarp was probably topographically positive during the Wolfcampian and allowed the dune field to develop. It diverted the flow of streams from the Uncompahgre uplift northward around its northern end and also formed the western boundary of a restricted embayment in which the coastal sabkha formed.

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